Higgs self-coupling study at ILC

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progress on λ_{HHH} study in 2012

- new weighting method to enhance the sensitivity of coupling (going to be published)
- study of the color-singlet jet clustering (very challenging)
- DBD benchmark: ZHH @ 500 GeV (preliminary)
- vvHH (fusion) @ 1TeV based on SGV fast simulation (done, going for the full simulation)
- summary and conclusion

reminder:

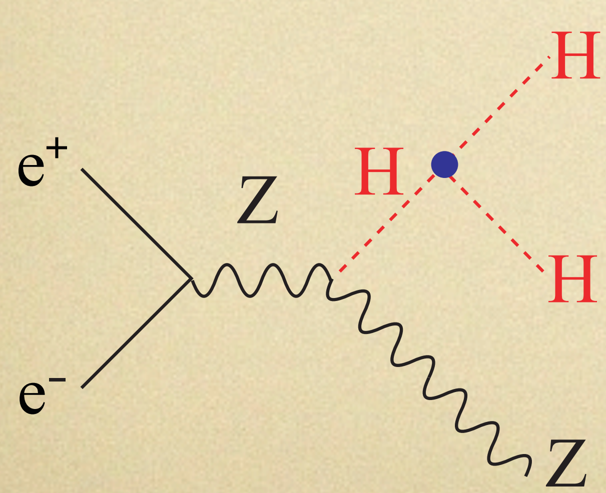
motivation of Higgs self-coupling measurement

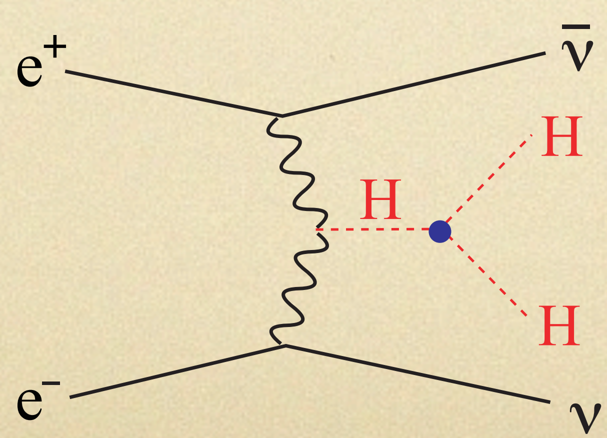
Higgs Potential: $V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda \upsilon \eta_H^3 + \frac{1}{4} \lambda \eta_H^4$

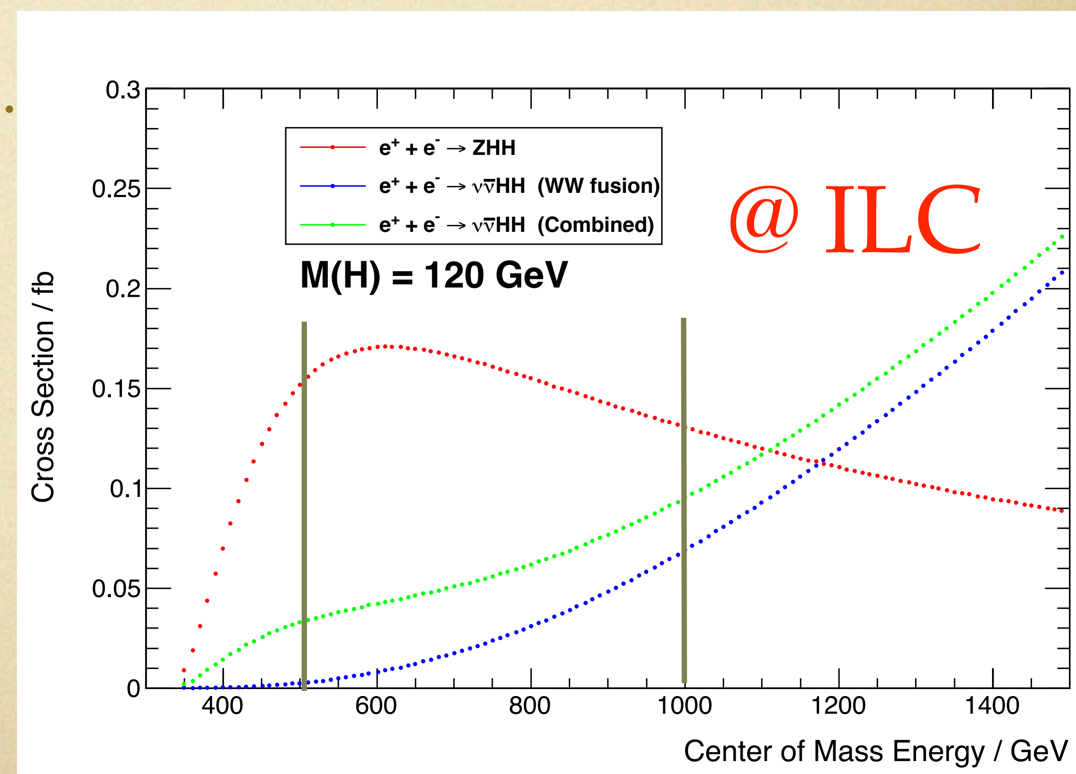
physical Higgs field — mass term — trilinear coupling — quartic Higgs coupling, which is difficult to measure at both LHC and ILC, even SLHC!

SM: $\lambda = \lambda_{SM} = \frac{m_H^2}{2\upsilon^2}$ $\upsilon \sim 246$ GeV

- just the force that makes the Higgs boson condense in the vacuum (a new force, non-gauge interaction).
- direct determination of the Higgs potential.
- accurate test of this coupling may reveal the extended nature of Higgs sector, like THDM and SUSY.
- difficult to measure at LHC for a light Higgs.







difficulties

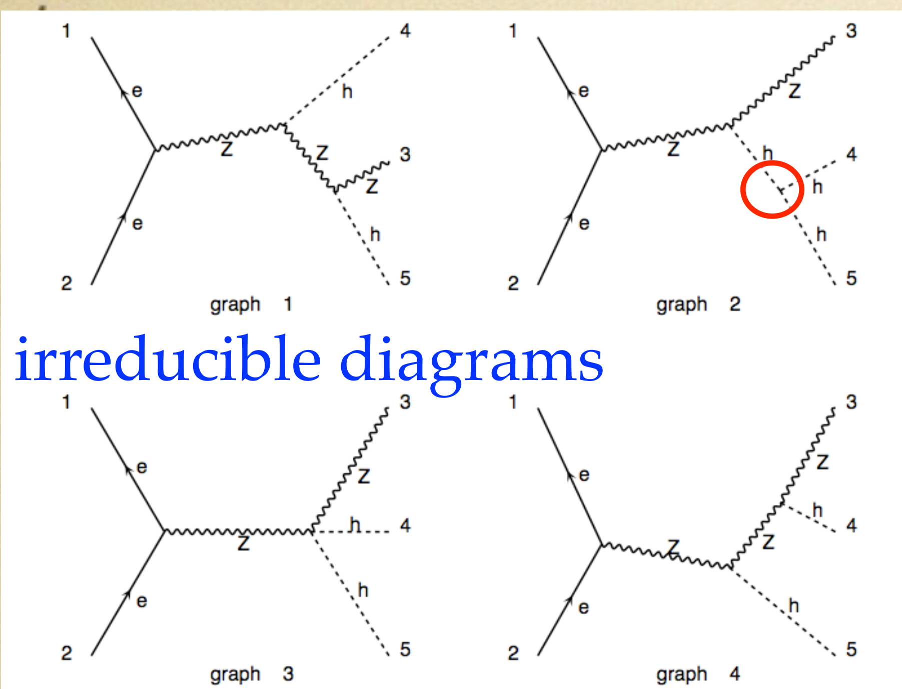
fundamental:

- irreducible SM diagrams, significantly degrade the coupling sensitivity.
- very small cross section (σ_{ZHH}~0.22 fb with P_L) and we are only using ~40% of the signal (both H-->bb). large integrated luminosity needed.
- huge SM background (tt/WWZ, ZZ/Zγ, ZZZ/ZZH), 3-4 orders higher.

strategic:

- Higgs mass reconstruction: mis-clustering, missing neutrinos, wrong pairing.
- flavor tagging and isolated-lepton selection: need very high efficiency and purity.
- neural-net training: separated neural-nets, huge statistics needed.

new weighting method to enhance the coupling sensitivity

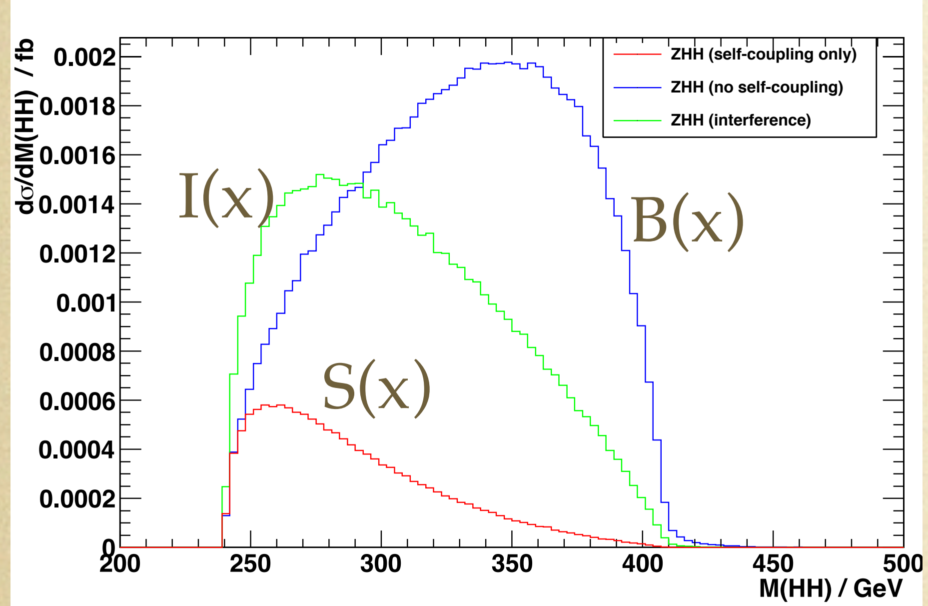


$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

irreducible — interference — self-coupling

observable: weighted cross-section

$$\sigma_w = \int \frac{\mathrm{d}\sigma}{\mathrm{d}x} w(x) \mathrm{d}x$$

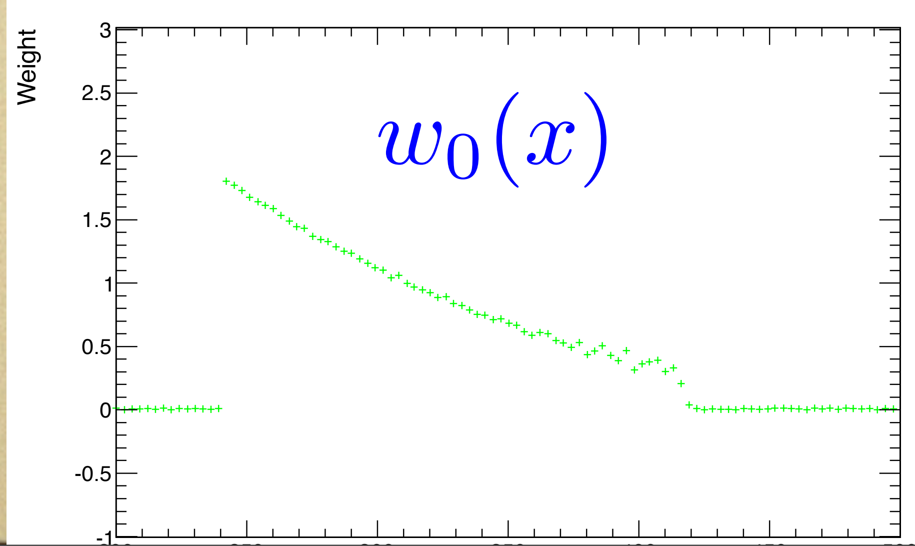


equation of the optimal w(x):

$$\sigma(x) w_0(x) \int (I(x) + 2S(x)) w_0(x) \mathrm{d}x = (I(x) + 2S(x)) \int \sigma(x) w_0^2(x) \mathrm{d}x$$

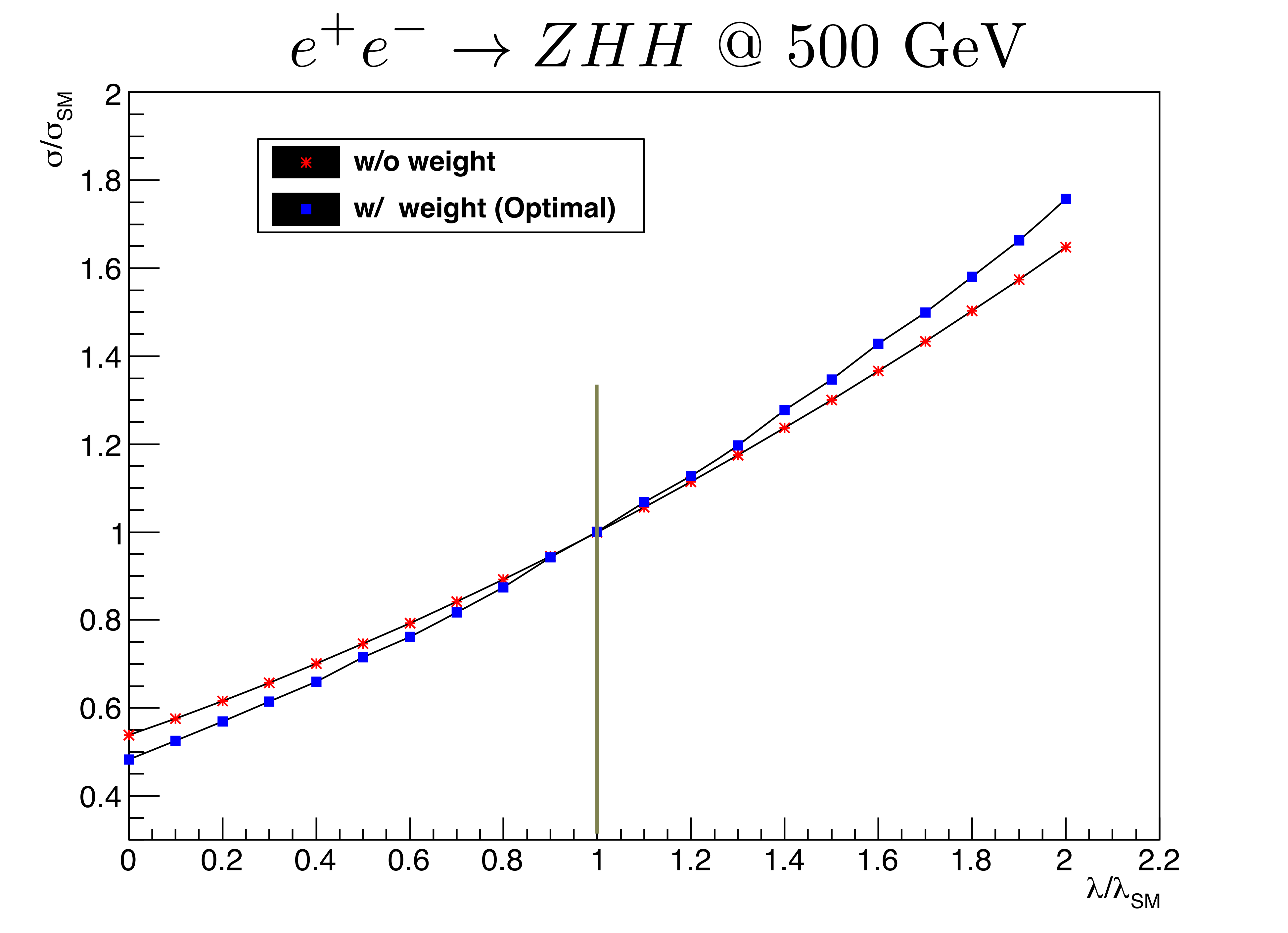
general solution:

$$w_0(x) = c \cdot \frac{I(x) + 2S(x)}{\sigma(x)}$$



c: arbitrary normalization factor

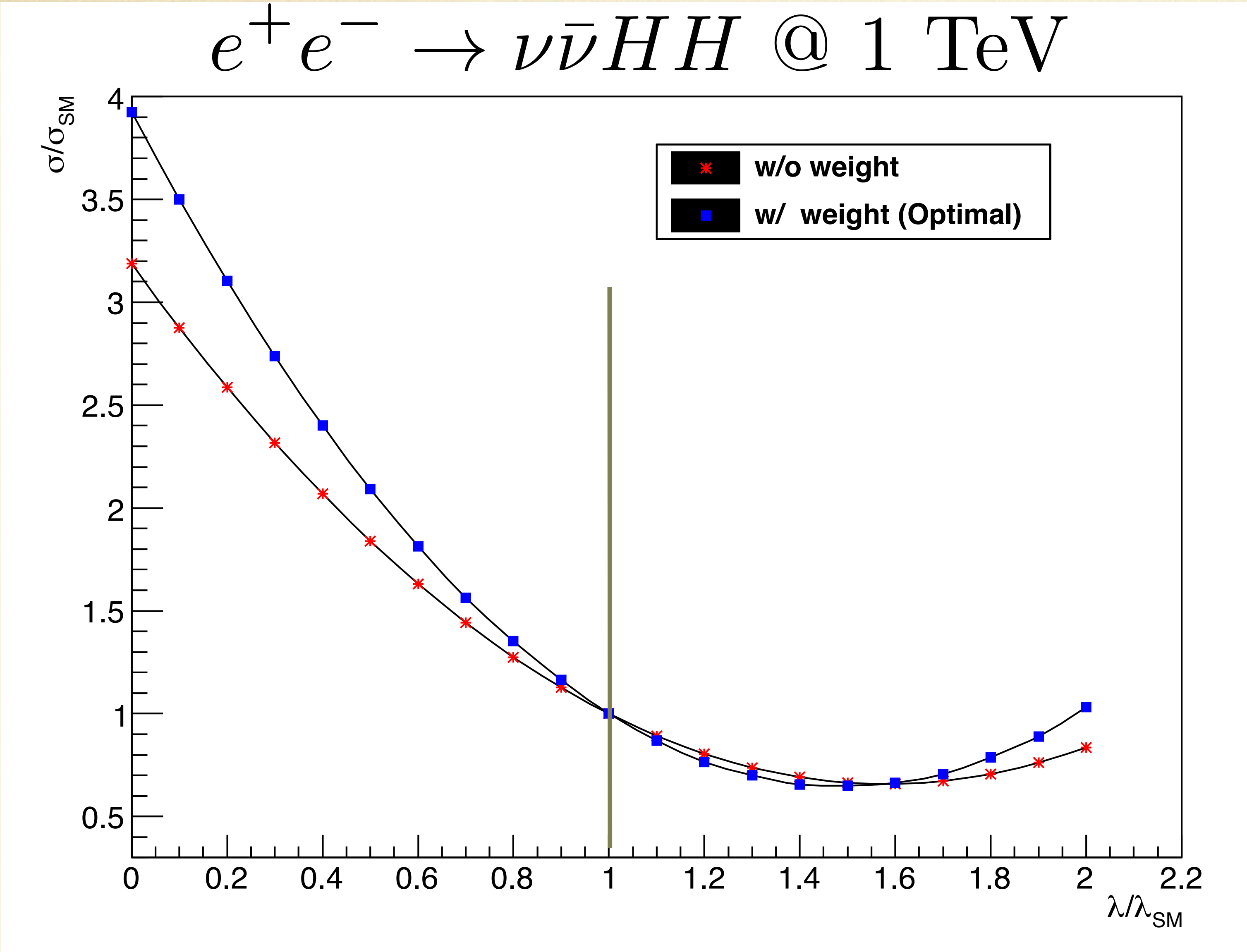
sensitivity

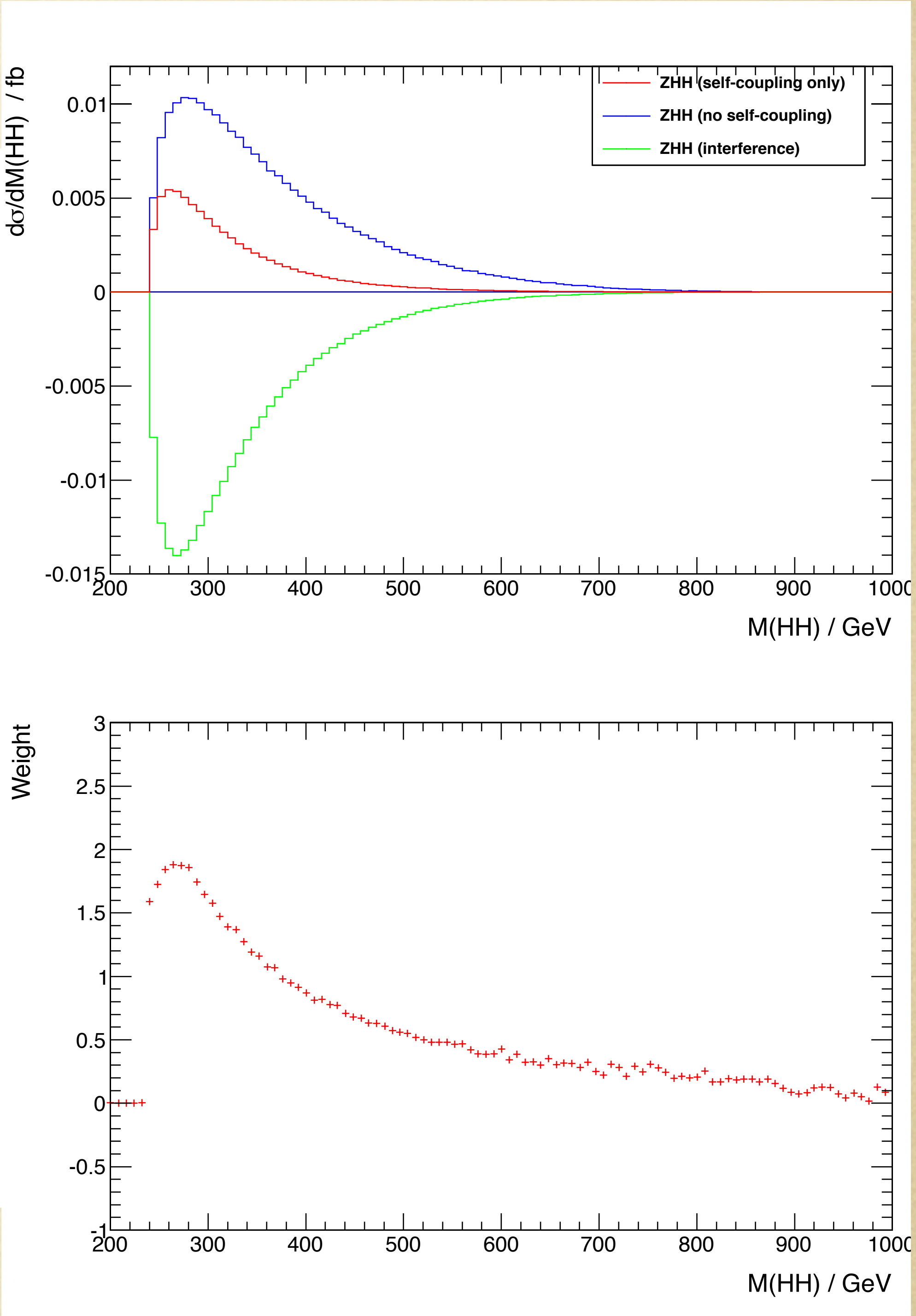


$$\frac{\Delta\lambda}{\lambda} = 1.80\frac{\Delta\sigma}{\sigma}$$

$$\frac{\Delta\lambda}{\lambda} = 1.57\frac{\Delta\sigma_w}{\sigma_w} = 1.66\frac{\Delta\sigma}{\sigma}$$

sensitivity





$$\frac{\Delta\lambda}{\lambda} = 0.85\frac{\Delta\sigma}{\sigma}$$

$$\frac{\Delta\lambda}{\lambda} = 0.69\frac{\Delta\sigma_w}{\sigma_w} = 0.76\frac{\Delta\sigma}{\sigma}$$

analysis strategy and status

$$e^+ + e^- \to ZHH\ @\ 500\ GeV$$

main backgrounds in each mode:

- llHH: llbb (ZZ, γZ, bbZ), lνbbqq (tt-bar), llbbbb (ZZZ/ZZH)
- ννHH: bbbb (ZZ, γZ, bbZ), τνbbqq (tt-bar), ννbbbb (ZZZ/ZZH)
- qqHH: bbbb (ZZ, γZ, bbZ), bbqqqq (tt-bar), qqbbbb (ZZZ/ZZH)

after isolated-lepton selection (or rejection) and jet-clustering, a neural-net is trained for each dominant background process (in total 9)

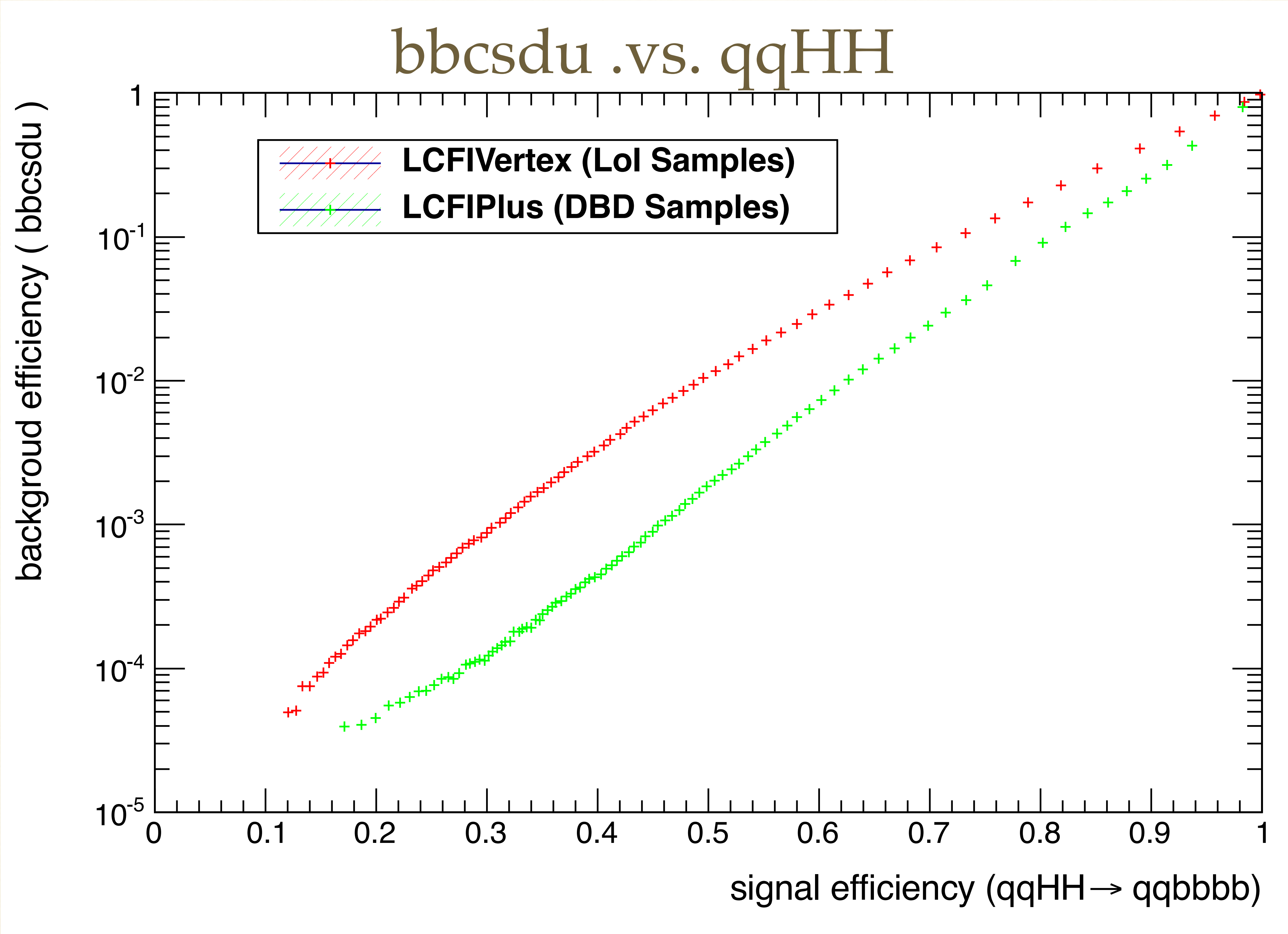
to make the result stable, high statistics (~10 ab^{-1}) is used

main improvements to the LoI analysis:

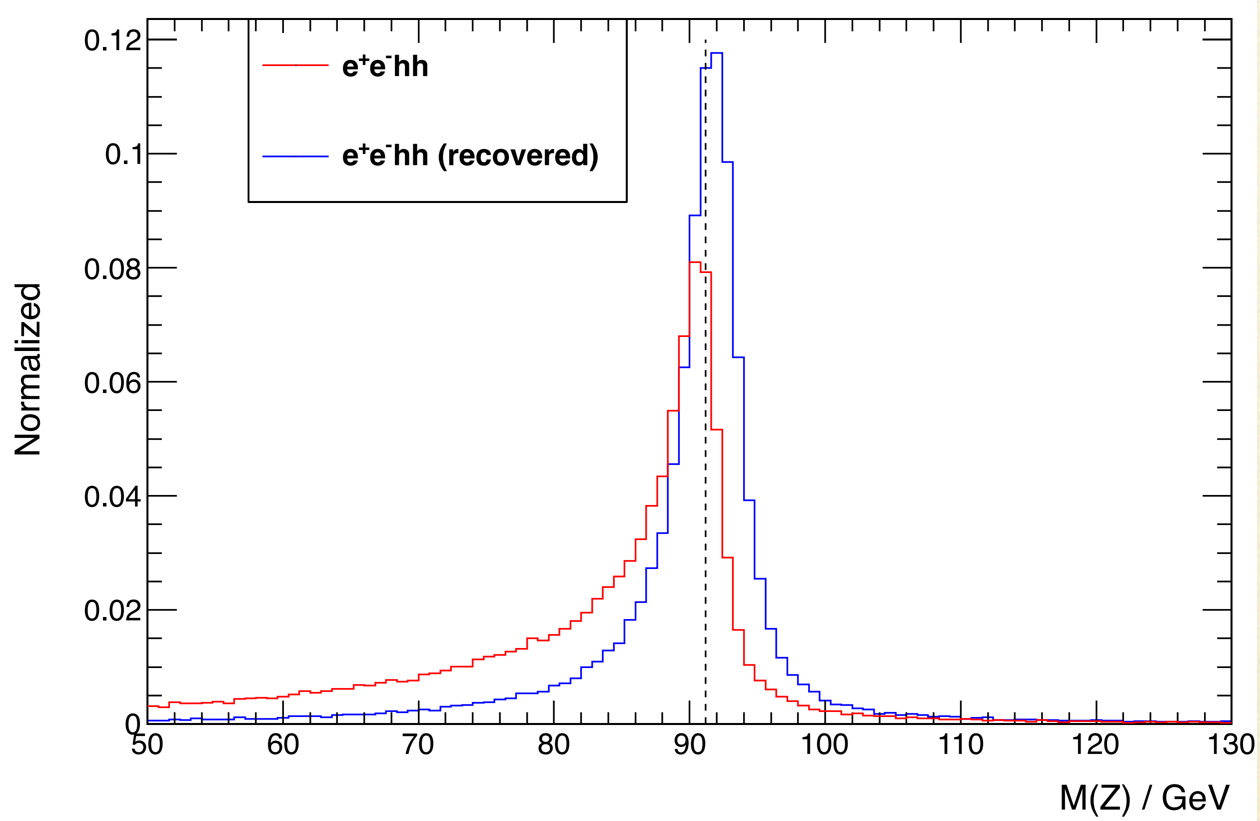
- better flavor tagging (tracking, PFA, LCFIPlus, B-baryon fixed)
- better lepton selection (muon detector, vertex constrained, bremsstrahlung and FSR recovered)

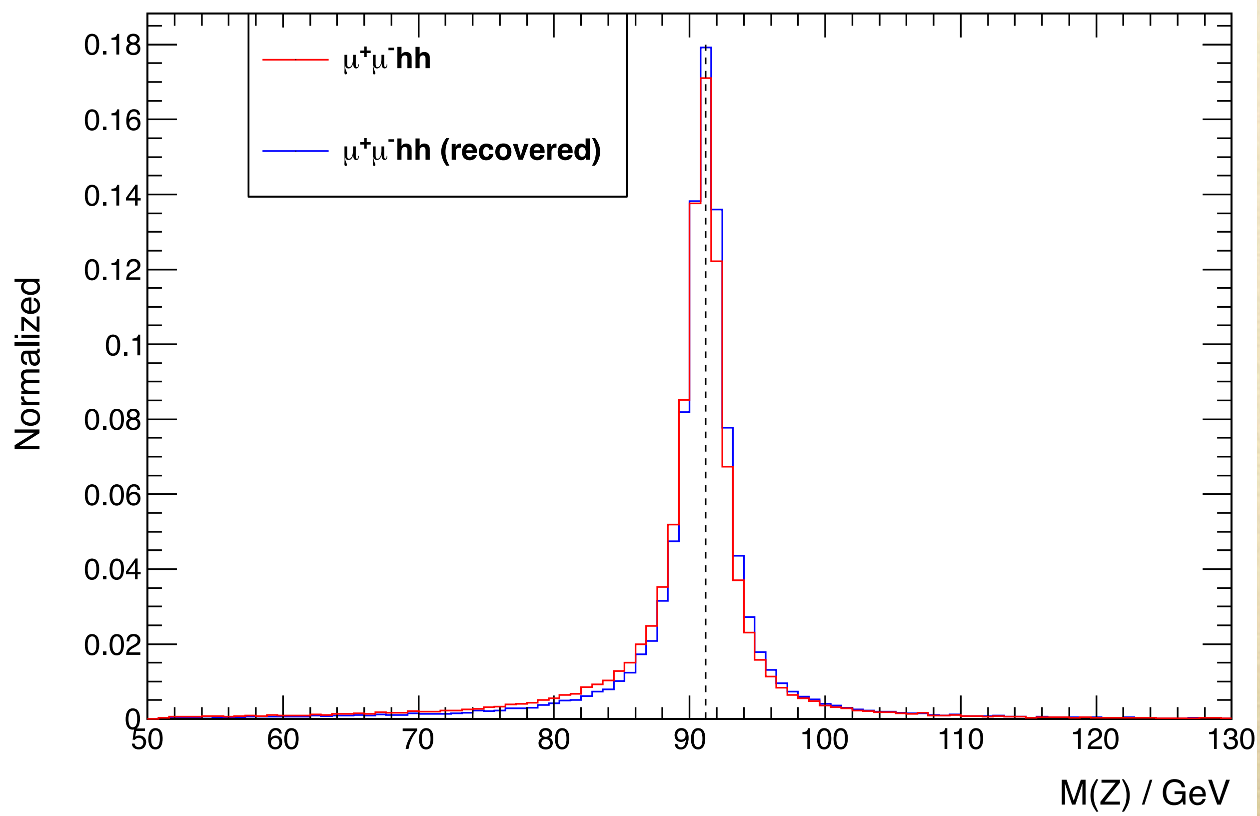
flavor tagging performance in qqHH mode

Thanks to developers of LCFIPlus (T. Tanabe and T. Suehara)



Isolated lepton selection (llHH)





(Etot = Eecal + Ehcal)

	electron ID	muon ID
✦	Eecal / Etot > 0.9	Eyoke > 1.2
✦	0.5 < Etot / P < 1.3	Etot / P < 0.3
✦	from primary vertex	from primary vertex
✦	P > 12.2 + 0.87Econe	P > 12.6 + 4.62Econe

BS and FSR recovery adapted from ZFinder

efficiency of two isolated lepton selection
(much better for DBD)

Eff (%)	eeHH	μμHH	bbbb	eνbbqq	μνbbqq
DBD	85.7	88.4	0.028	1.44	0.10
LoI	81.9	85.4	0.43	2.71	1.94

$$e^+ + e^- \rightarrow ZHH \rightarrow (q\bar{q})(b\bar{b})(b\bar{b}) \rightarrow q\bar{q} + 4 \text{ bjets}$$

full simulation @ 500GeV

pre-selection:

✦generator: Whizard 1.95
✦simulation: ilcsoft-v01-14-01
✦reconstruction: ilcsoft-v01-16
✦flavor tagging: LCFIPlus

- isolated-charged-leptons rejected
- 6-jets clustering (LCFIPlus, Durham)
- combine the six jets by minimizing, and require the b tagging

$$\chi^2 = \frac{(M(b,\bar{b}) - M_H)^2}{\sigma_{H_1}^2} + \frac{(M(b,\bar{b}) - M_H)^2}{\sigma_{H_2}^2} + \frac{(M(q,\bar{q}) - M_Z)^2}{\sigma_Z^2}$$

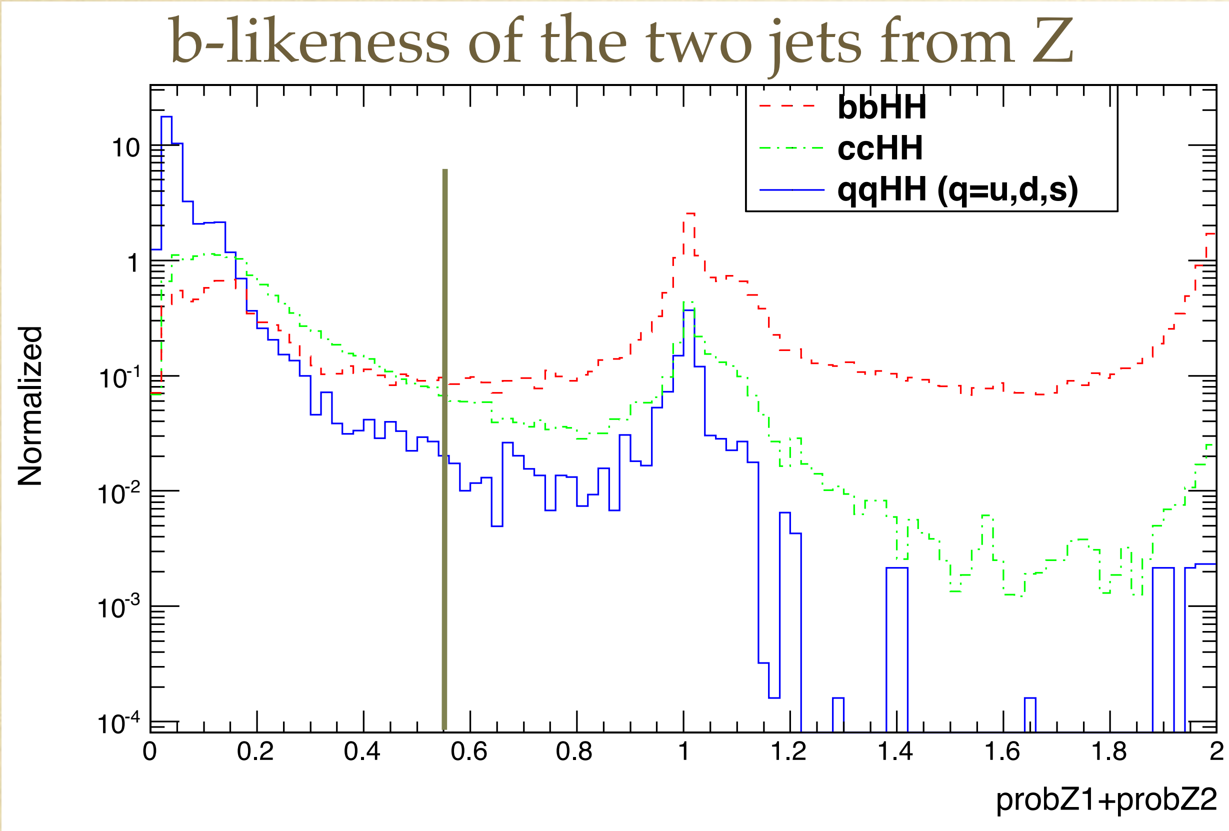
requirement implied in the pre-selection:

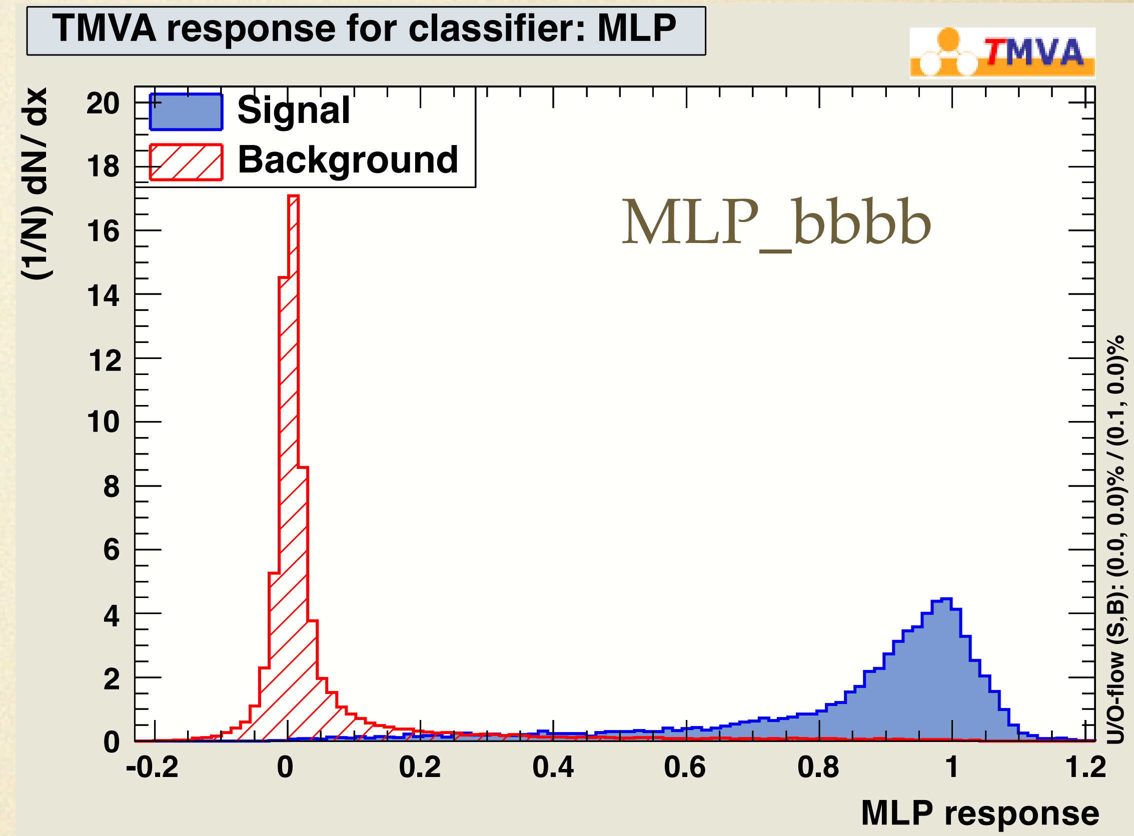
- b-tagged four jets from two Higgs (b-likeness > 0.16)

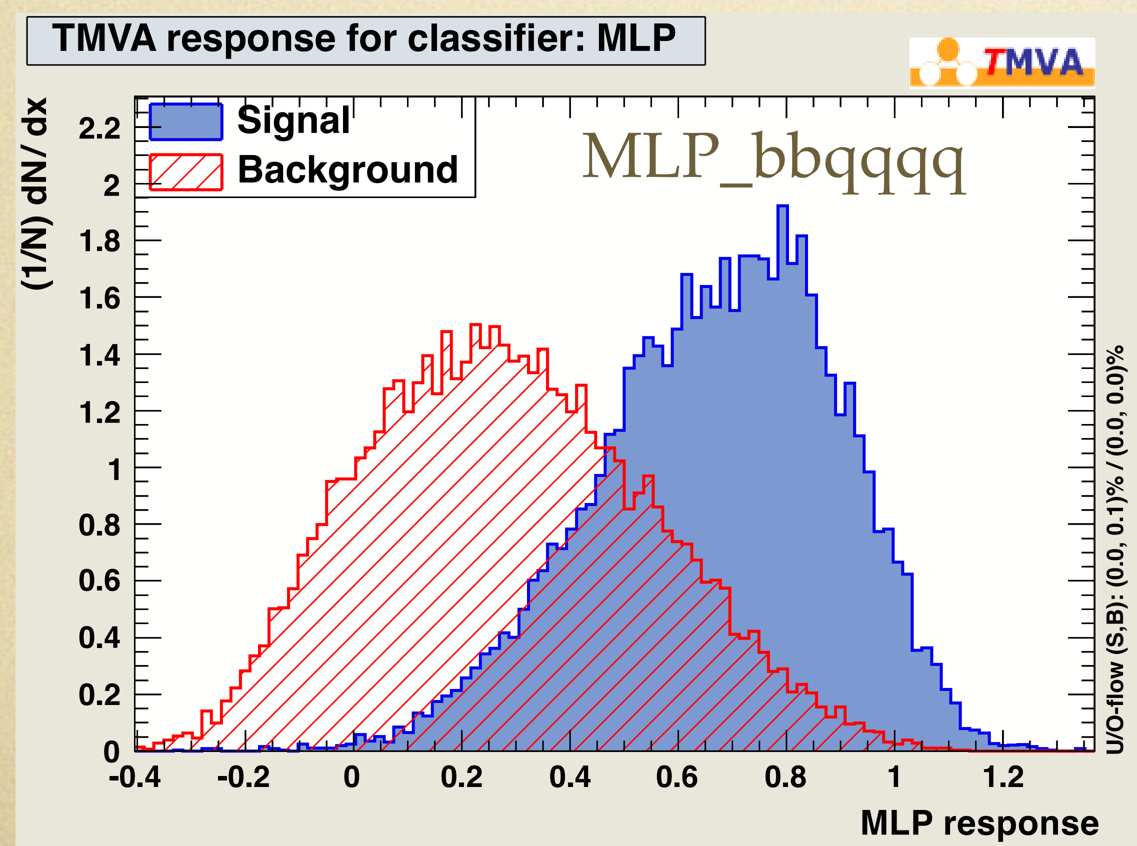
final selection:

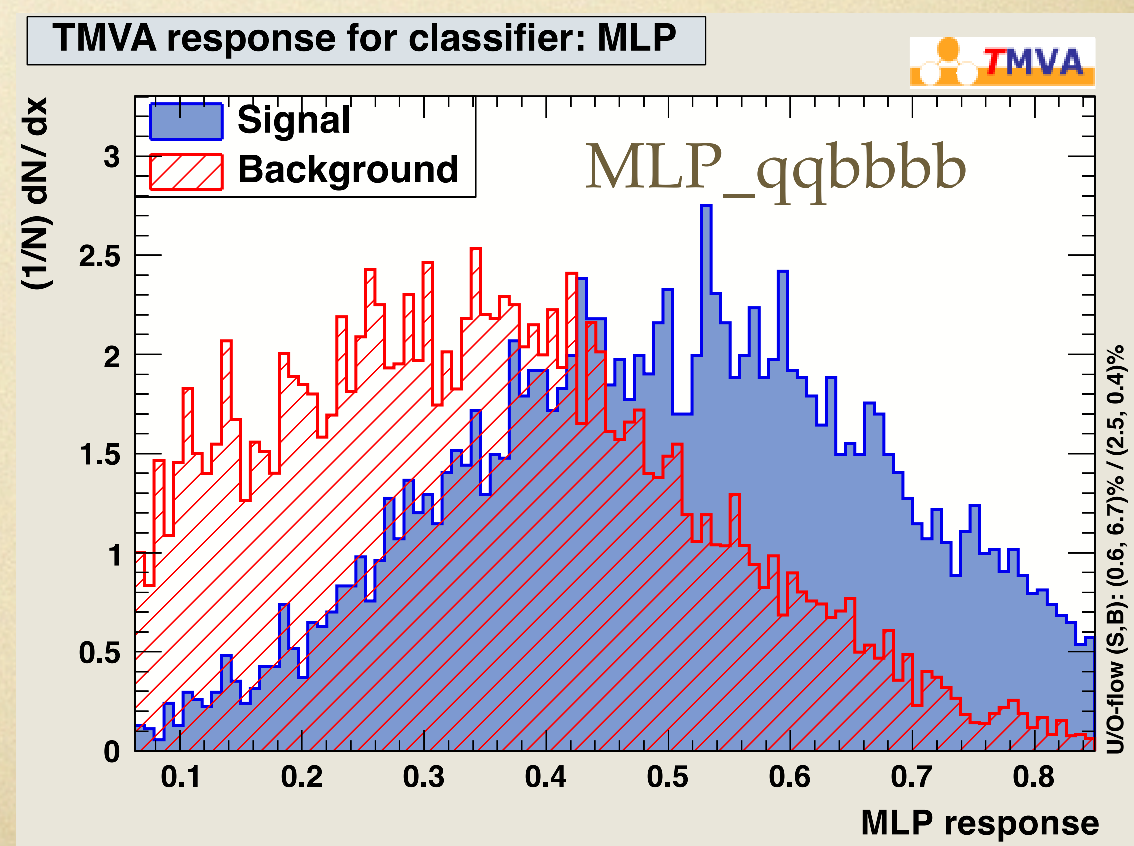
- separate to two categories: bbHH dominant and light qqHH dominant
- train the neural-nets, each event is also reconstructed as from ZZ, tt-bar, ZZZ and ZZH, and various variables are input to NN
- optimize the cuts on NN-output and tighter b-tagging

some distributions









preliminary

reduction table

(probZ1+probZ2 > 0.54)

P(e-,e+)=(-0.8,+0.3)

$E_{\rm cm} = 500{\rm GeV}, M_H = 120{\rm GeV}$

$\int Ldt = 2{\rm ab}^{-1}$

normalized	expected	MC	pre-selection	probZ1+probZ2>0.54	MissPt < 60 Mass Cut	MLP_bbbb>0.47	MLP_bbqqqq>0.33	MLP_qqbbbb>0.16	Bmax3+Bmax4 >1.17
qqhh(qqbbbb)	310(129)	3.73×10^5	111(85.3)	26.9(23.2)	25.1(22.3)	23.0(20.9)	22.4(20.4)	21.1(19.2)	13.6(13.0)
bbbb	4.02×10^4	7.19×10^5	22889	2319	733	16.5	15.0	11.8	5.25
lvbbqq	7.40×10^5	3.56×10^6	17240	363	103	18.7	15.9	12.8	0.03
qqbbbb	140	1.23×10^5	82.9	13.9	12.7	9.80	9.19	5.78	3.03
bbuddu	1.56×10^5	8.87×10^5	565	11.4	11.3	10.0	7.65	6.92	0.55
bbcsdu	3.12×10^5	1.26×10^6	6109	89.0	78.4	67.6	51.2	45.1	1.01
bbcssc	1.56×10^5	1.17×10^6	12456	263	246	212	147	129	3.69
qqqqH(ZZH)	818	5.98×10^4	154	27.5	25.4	22.5	21.6	18.5	10.9
ttz	2.20×10^3	8.49×10^4	172	17.2	13.6	12.5	12.3	11.4	2.88
ttbb	2.11×10^3	8.25×10^4	450	47.8	29.9	26.0	24.5	22.6	3.40
BG			60119	3152	1253	395	304	264	30.7

bbHH dominant: nS = 13.6, nB = 30.7 ~ 2.0σ

preliminary

P(e-,e+)=(-0.8,+0.3)

reduction table

(probZ1+probZ2 < 0.54)

$E_{\text{cm}} = 500\text{GeV}, M_H = 120\text{GeV}$

$\int Ldt = 2\text{ab}^{-1}$

normalized	expected	MC	pre-selection	probZ1+probZ2<0.54	MissPt < 60 Mass Cut	MLP_bbbb>0.48	MLP_bbqqqq>0.51	MLP_qqbbbb>0.09	Bmax3>0.85 Bmax3+Bmax4 >1.21
qqhh(qqbbbb)	310(129)	3.73×10^5	111(85.3)	84.0(62.1)	36.9(31.4)	34.2(29.4)	31.0(26.9)	30.8(26.6)	18.8(17.0)
bbbb	4.02×10^4	7.19×10^5	22889	20570	273	22.0	18.1	17.2	10.0
lvbbqq	7.40×10^5	3.56×10^6	17240	16877	408	147	74.0	73.2	1.07
qqbbbb	140	1.23×10^5	82.9	68.9	11.1	9.49	7.92	6.95	4.07
bbuddu	1.56×10^5	8.87×10^5	565	554	102	96.7	48.4	47.9	5.93
bbcsdu	3.12×10^5	1.26×10^6	6109	6020	1200	1094	501	492	15.7
bbcssc	1.56×10^5	1.17×10^6	12456	12193	2308	2111	848	829	16.0
qqqqH(ZZH)	818	5.98×10^4	154	126	37.8	34.0	30.5	29.9	16.1
ttz	2.20×10^3	8.49×10^4	172	155	30.3	29.4	25.7	25.5	7.74
ttbb	2.11×10^3	8.25×10^4	450	402	62.4	59.3	49.0	48.6	14.0
BG			60119	56967	4433	3603	1603	1570	90.6

light qqHH dominant: nS = 18.8, nB = 90.6 ~ 1.8σ

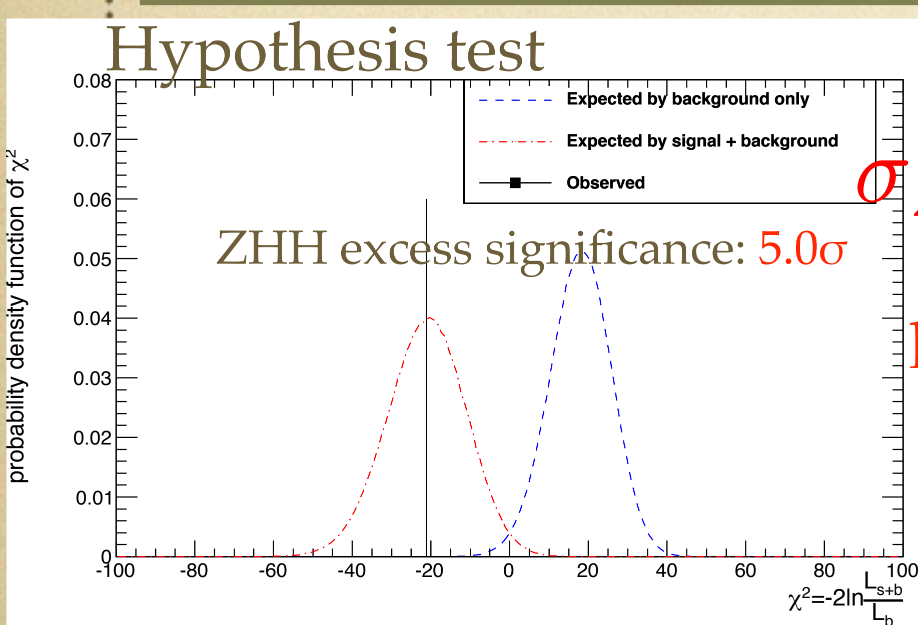
Status of DBD analysis

preliminary

P(e-,e+)=(-0.8,0.3) $e^+ + e^- \to ZHH$ $M(H) = 120\text{GeV}$ $\int Ldt = 2\text{ab}^{-1}$

Energy (GeV)	Modes	signal	background	significance	
				excess (I)	measurement (II)
500	$ZHH \to (l\bar{l})(b\bar{b})(b\bar{b})$	3.7	4.3	1.5σ	1.1σ
		4.5	6.0	1.5σ	1.2σ
500	$ZHH \to (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	8.5	7.9	2.5σ	2.1σ
500	$ZHH \to (q\bar{q})(b\bar{b})(b\bar{b})$	13.6	30.7	2.2σ	2.0σ
		18.8	90.6	1.9σ	1.8σ

Hypothesis test

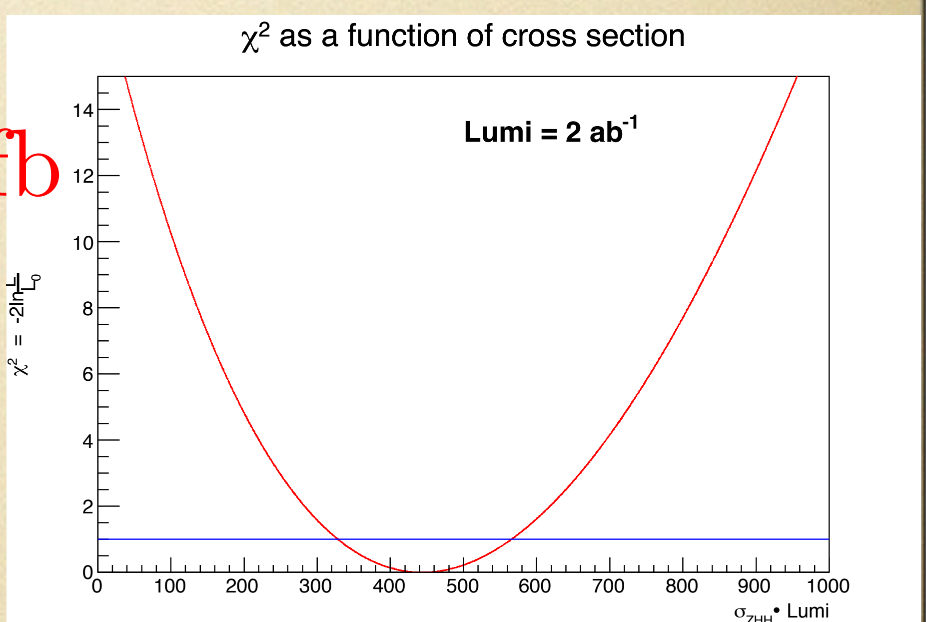


ZHH excess significance: 5.0σ

$$\sigma_{ZHH} = 0.22 \pm 0.06 \quad \text{fb}$$

precision of cross section: **27%**

Higgs self-coupling: **48%**



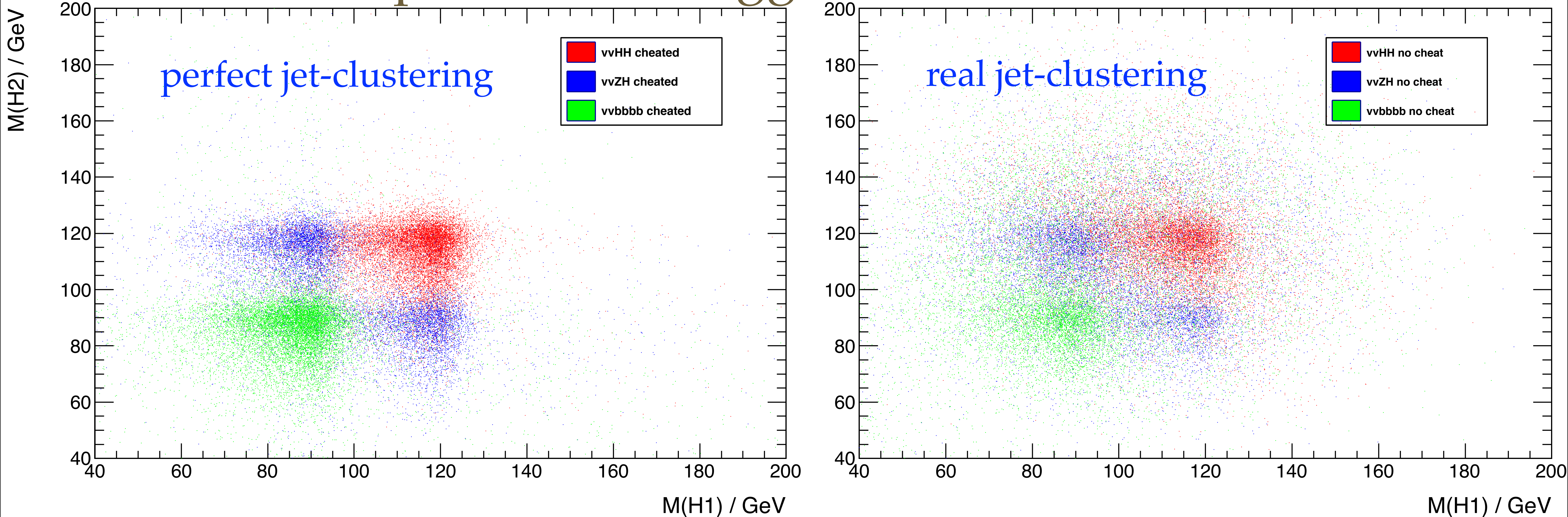
after using weighting, would be: $\frac{\delta\lambda}{\lambda} = 44\%$

Color-singlet Jet Finder

(project under developing)

- the mis-clustering of particles degrades the mass resolution very much
- it is studied using perfect color-singlet jet-clustering can improve $\delta\lambda$ ~ 40%

scatter plot of two Higgs masses vvHH mode: (ZZH and ZZZ)



- Mini-jet based clustering (Durham works when Np in mini-jet ~ 5, need better algorithm to combine the mini-jets, using such as color-singlet dynamics)
- looks very challenging now...

$$e^+ + e^- \to \nu\bar{\nu}HH \to \nu\bar{\nu}(b\bar{b})(b\bar{b})$$

SGV fast simulation @ 1 TeV

- ✦generator: Whizard 1.95 (DBD)
- ✦simulation: SGV (ILD_00)
- ✦reconstruction: ilcsoft-v01-15

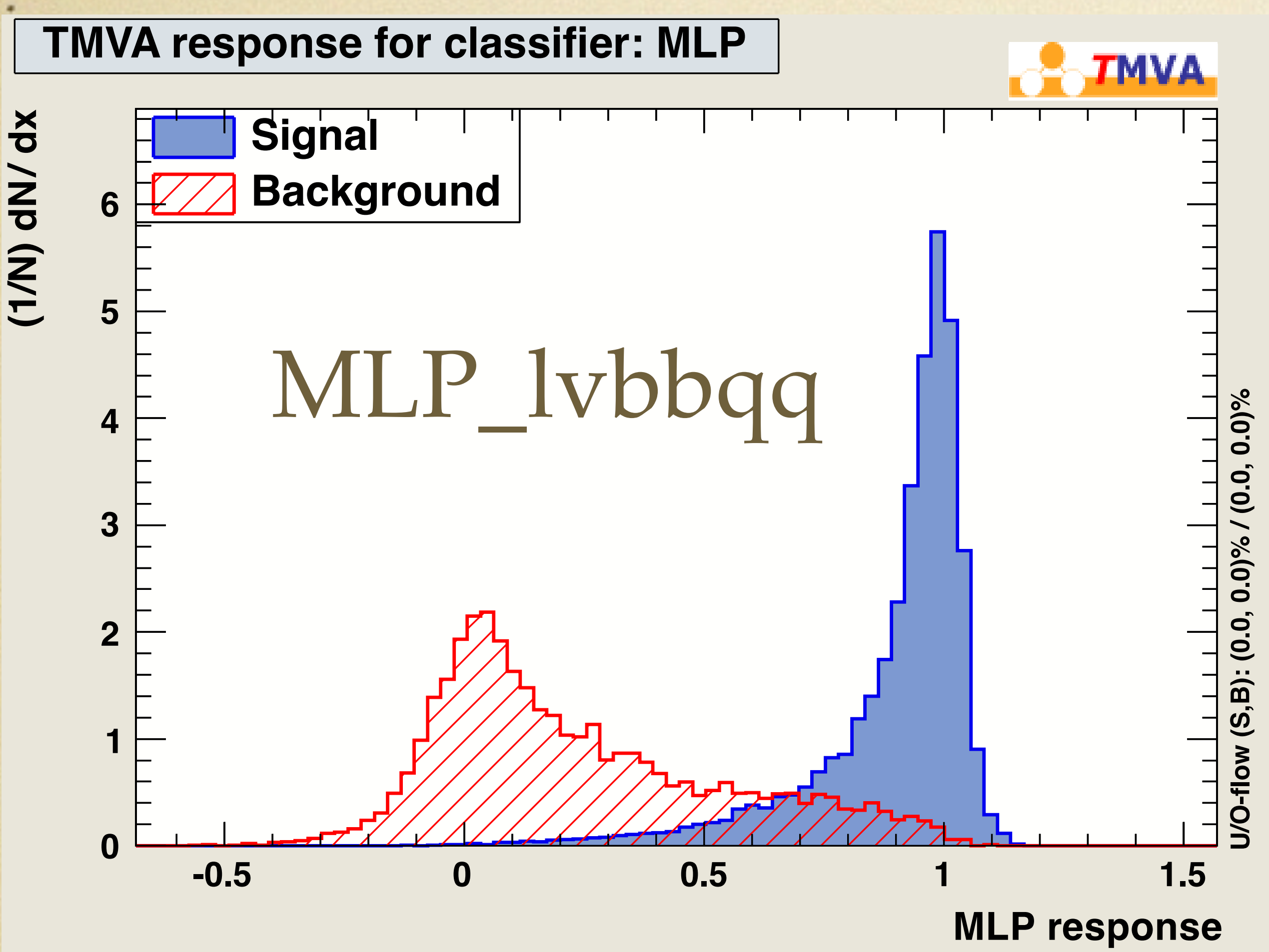
pre-selection:

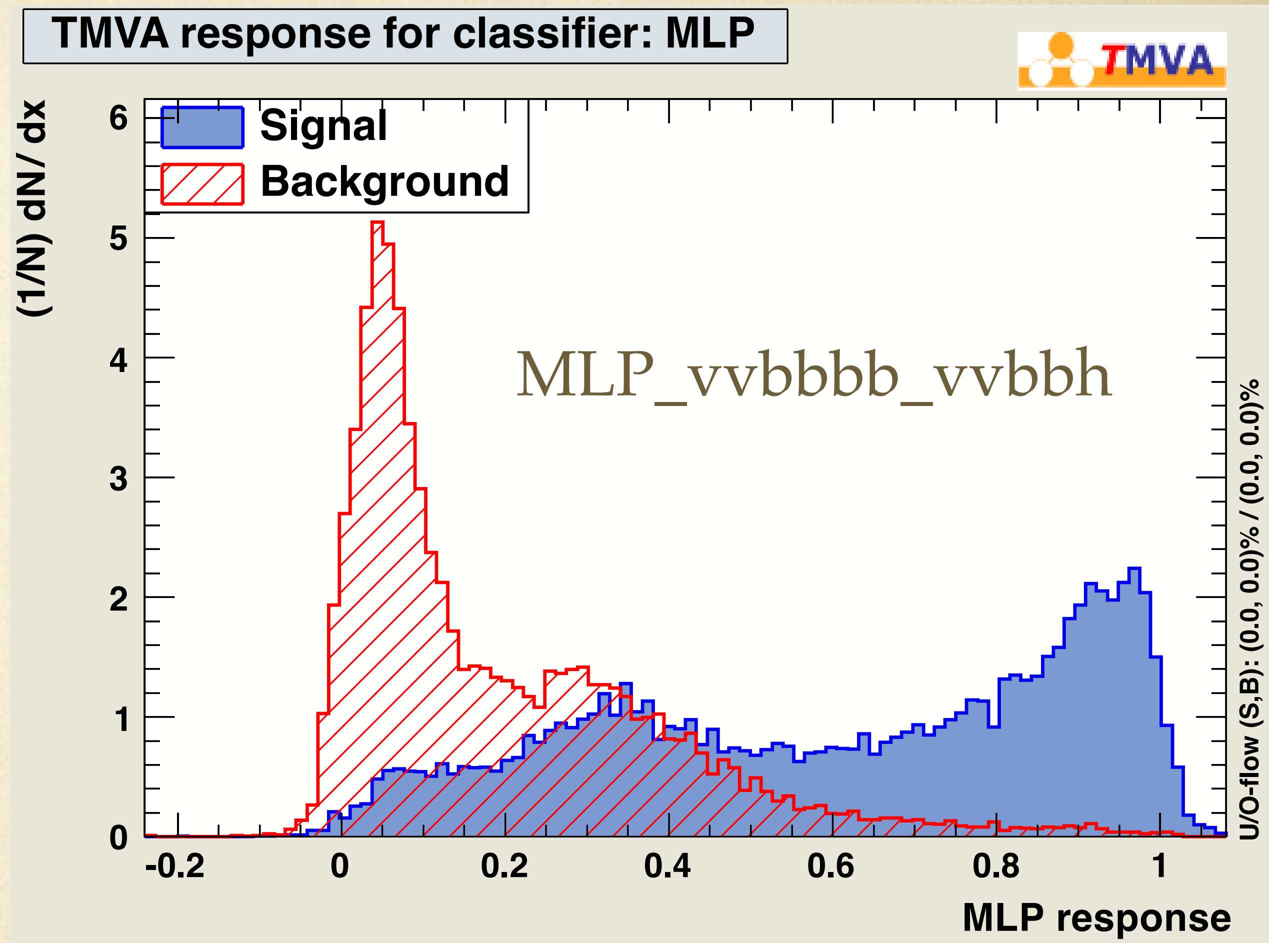
- no isolated lepton, ISR tag
- four jets, each with more than 8 particles, 3rd Btagging > 0.2

final-selection:

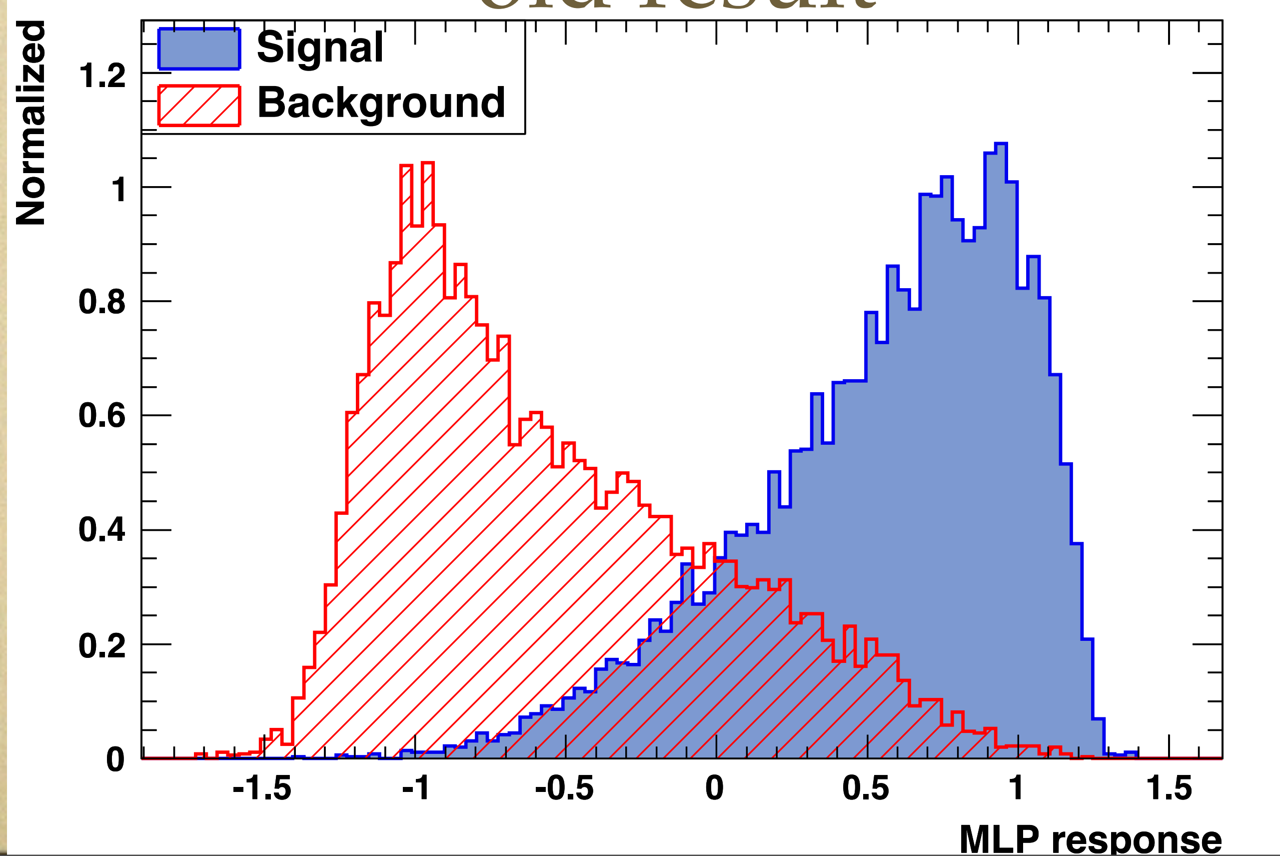
- Visible energy: Evis < 500 + 3*MissPt, Pt > 10 GeV (cut1)
- Missing mass (Z rejection): > 200 GeV (cut2)
- tt-bar suppression: MLP_lvbbqq > 0.82 (cut3)
- vvZZ and vvZH suppression: MLP_vvbbbb > 0.59 (cut4)
- B-tagging: Bmax3 > 0.49 (cut5)

Neural-net output

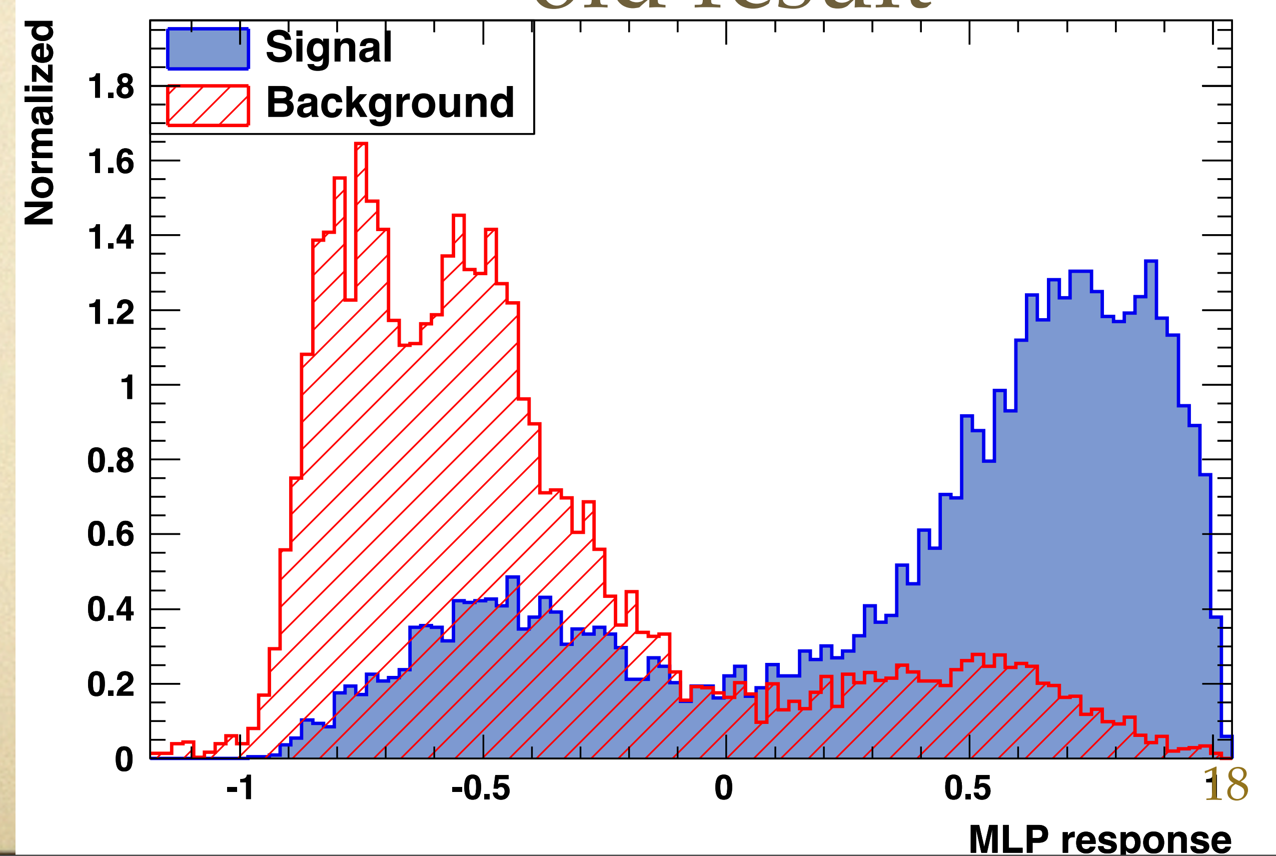




old result



old result



signal and backgrounds (reduction table)

preliminary

Polarization: (e-,e+)=(-0.8,+0.2) $E_{\rm cm} = 1$ TeV, $M_H = 120$ GeV $\int L = 2\ {\rm ab}^{-1}$

	Expected	Generated	pre-selction	cut1	cut2	cut3	cut4	cut5
ννhh (WW F)	272	9.20×10^4	104	97.9	96.5	75.8	44.8	35.6
ννhh (ZHH)	74.0	4.76×10^5	26.8	17.9	14.7	7.15	4.46	3.67
ννbbbb	650	4.43×10^5	481	466	459	162	4.18	3.28
ννccbb	1070	5.10×10^5	200	193.6	189	64.4	1.56	0.22
bbxyyx	2.92×10^5	1.05×10^6	14102	563	530	20.6	12.4	0.91
eνbbqq	1.16×10^5	6.22×10^5	620	462	353	34.6	6.42	0.83
μνbbqq	1.08×10^5	6.39×10^5	366	255	196	10.1	2.25	0.49
τνbbqq	1.08×10^5	6.37×10^5	3502	2184	1741	104	33.9	4.47
ννZH	3125	5.00×10^4	449	441	439	296	21.4	13.1
ttH	6952	1.00×10^5	88.6	59.7	55.1	1.40	0.96	0.68
BG	6.37×10^5		19835	4643	3978	701	87.4	27.6
significance	0.34		0.74	1.42	1.51	2.72	3.90	4.48

$$\frac{\Delta\sigma}{\sigma} \approx 22\% \qquad \frac{\Delta\lambda}{\lambda} \approx 19\% \quad (17\%)$$

Summary

- a new general weighting method developed, ~10% improvement for coupling.
- better flavor tagging and lepton ID performance for DBD simulations and reconstruction, ~20% improvement for analysis.
- DBD full simulation: ZHH @ 500 GeV, P(e-,e+)=(-0.8,+0.3), 2 ab^{-1}, M(H)=120GeV, $\delta\sigma/\sigma$ ~ 27%, $\delta\lambda/\lambda$ ~ 44%.
- SGV fast simulation: $\nu\nu$HH @ 1 TeV, P(e-,e+)=(-0.8,+0.2), 2 ab^{-1}, M(H)=120GeV, $\delta\sigma/\sigma$ ~ 22%, $\delta\lambda/\lambda$ ~ 17%.
- similar result for M(H)=125GeV may be achieved by including HH-->bbWW* (Br. ~25%), now being investigated by M. Kurata (Tokyo U')
- color-singlet jet-clustering could significantly improve the ZZZ/ZZH suppression, under developing.

To do...

- vvHH @ 1 TeV based on full simulation
- draft current result (LC Note and Publish?)
- kinematic fitting, color-singlet jet clustering

backup

preliminary

P(e-,e+)=(-0.8,+0.3)

reduction table

$E_{cm} = 500\text{GeV}, M_H = 120\text{GeV}$

(muon-type)

$\int Ldt = 2\text{ab}^{-1}$

normalized	expected	MC	pre-selection	ltype = 13	Econ12+4EconC12<60 PLep1+PLep2>80 $\vert M(ll)-M(Z)\vert<27$	MLP_llbb>0.53	MLP_lvbbqq>0.2	Bmax3>0.16	MLP_llbbbb>0.52
llhh(llbbbb)	46.5(19.3)	3.88×10^5	26.5(11.0)	13.3(5.53)	13.0(5.38)	10.6(5.24)	10.4(5.23)	5.76(4.79)	4.47(3.76)
eebb	2.84×10^5	4.18×10^6	3950	0	0	0	0	0	0
μμbb	4.96×10^4	1.00×10^6	1944	1943	1750	73.3	72.8	7.28	2.33
eνbbqq	2.48×10^5	1.51×10^6	2437	0	0	0	0	0	0
μνbbqq	2.46×10^5	1.48×10^6	239	215	95.7	65.7	33.3	2.78	0
τνbbqq	2.46×10^5	1.35×10^6	156	7.76	2.62	1.82	0.80	0	0
bbqqqq	6.24×10^5	3.90×10^6	107	1.09	0	0	0	0	0
bbbb	4.02×10^4	1.02×10^6	5.84	0.08	0	0	0	0	0
llbbbb(ZZZ)	69.5	1.06×10^5	15.0	7.57	7.10	5.92	5.90	5.38	1.29
llqqh(ZZH)	157	6.30×10^4	138	69.7	68.4	54.3	54.0	12.8	2.36
BG	1.74×10^6	1.46×10^7	8992	2244	1924	201	167	28.2	5.97

muon-type: nS = 4.5, nB = 6.0 ~ 1.2σ

preliminary

P(e-,e+)=(-0.8,+0.3)

reduction table

$E_{\rm cm} = 500{\rm GeV}, M_H = 120{\rm GeV}$

(electron-type)

$\int Ldt = 2{\rm ab}^{-1}$

normalized	expected	MC	pre-selection	ltype = 11	Econ12+4EconC12<90 ∣M(ll)-M(Z)∣<32	MLP_llbb>0.56	MLP_lvbbqq>0.81	Bmax3>0.19	MLP_llbbbb >0.5
llhh(llbbbb)	46.5(19.3)	3.88×10^5	26.5(11.0)	13.1(5.50)	12.3(5.18)	10.1(5.02)	8.60(4.57)	4.64(4.08)	3.73(3.30)
eebb	2.84×10^5	4.18×10^6	3950	3950	2762	75.4	57.8	3.88	0.81
μμbb	4.96×10^4	1.00×10^6	1944	0.74	0.10	0	0	0	0
eνbbqq	2.48×10^5	1.51×10^6	2437	2437	928	675	25.7	1.93	0.46
μνbbqq	2.46×10^5	1.48×10^6	239	24.5	0.52	0.36	0	0	0
τνbbqq	2.46×10^5	1.35×10^6	156	148	38.6	30.3	1.50	0.25	0
bbqqqq	6.24×10^5	3.90×10^6	107	106	3.93	3.93	1.04	0.16	0.16
bbbb	4.02×10^4	1.02×10^6	5.84	5.76	0.10	0	0	0	0
llbbbb(ZZZ)	69.5	1.06×10^5	15.0	7.42	6.69	5.44	4.68	4.18	0.97
llqqh(ZZH)	157	6.30×10^4	138	68.1	65.0	51.1	46.9	9.92	1.93
BG	1.74×10^6	1.46×10^7	8992	6748	3806	842	138	20.3	4.32

electron-type: nS = 3.7, nB = 4.3 ~ 1.1σ

reduction table (vvHH)

Polarization: (e-,e+)=(-0.8,+0.3) $E_{\mathrm{cm}} = 500\mathrm{GeV}, M_H = 120\mathrm{GeV}$ $\int Ldt = 2\mathrm{ab}^{-1}$

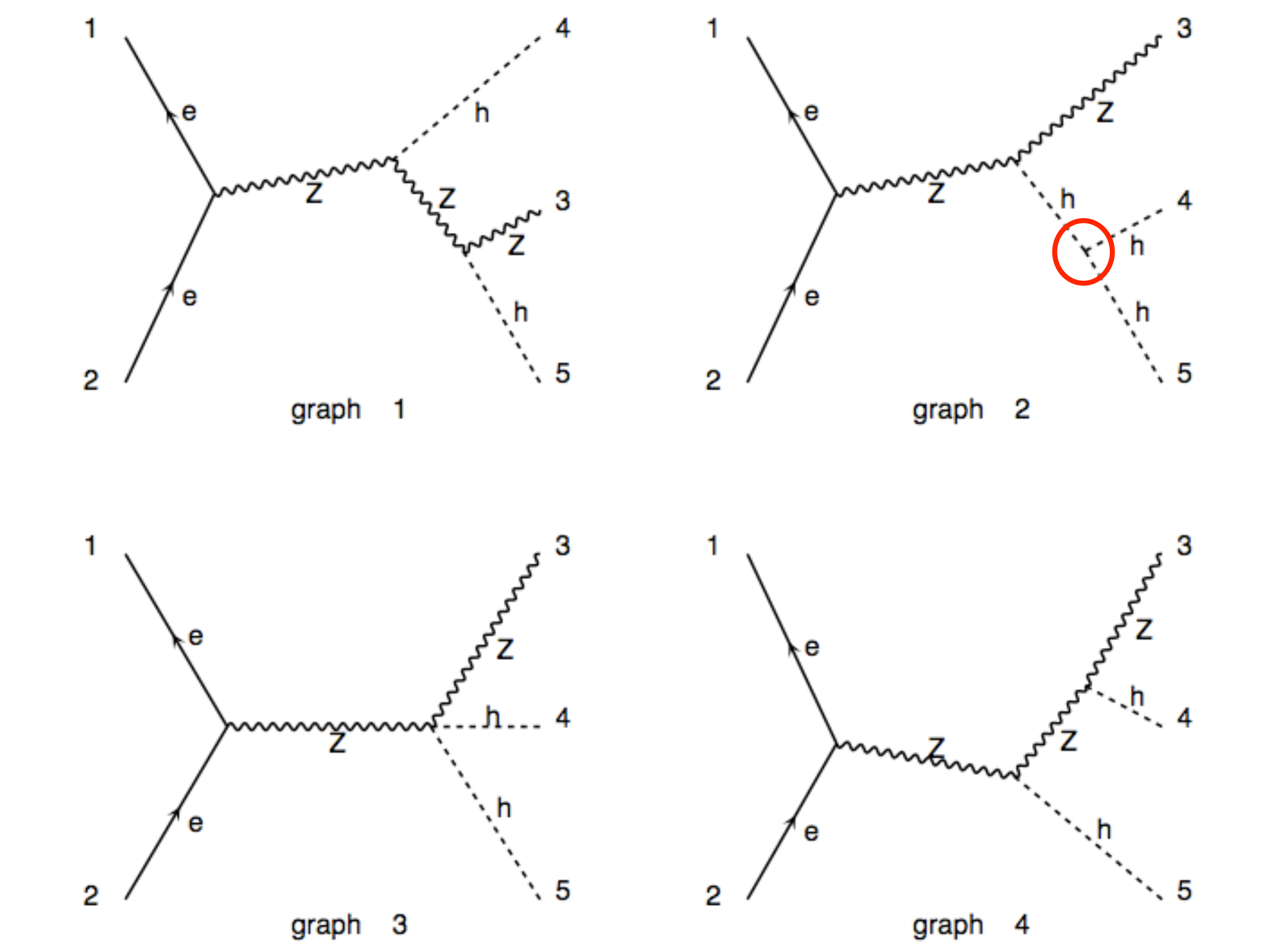
normalized	expected	MC	pre-selection	Evis-0.83MissPt <360 MissMass > 60	NpfosMin>=8 MassCut	MLP_bbbb>0.83	MLP_lvbbqq>0.56	MLP_vvbbbb>0.61	Bmax3+Bmax4 >1.14
ννhh(ννbbbb)	103(42.8)	7.06×10^5	45.0(37.0)	43.6(35.8)	26.0(23.7)	22.7(20.7)	20.6(18.9)	17.1(15.7)	8.47(8.42)
BG			1.33×10^5	33619	5887	4650	1176	887	7.86
ννbbbb	97.1	8.22×10^4	82.1	80.5	10.1	6.90	5.66	2.03	0.87
ννqqH(ZZH)	469	7.41×10^4	82.1	79.0	21.5	17.5	13.0	5.86	1.93
bbqqqq	6.24×10^5	3.88×10^6	58457	1212	178	71.5	38.6	37.2	0
bbbb	4.02×10^4	7.06×10^5	30826	3684	350	13.2	9.82	7.87	2.99
ννbb	2.73×10^5	4.79×10^5	861	758	9.17	4.25	4.25	3.02	0
eνbbqq	2.48×10^5	1.51×10^6	3884	2126	504	451	72.6	54.9	0
μνbbqq	2.46×10^5	1.48×10^6	1637	951	223	195	72.8	52.1	0
τνbbqq	2.46×10^5	1.59×10^6	37440	24728	2591	3890	959	724	2.07

nS = 8.5, nB = 7.9 ~ 2.1σ

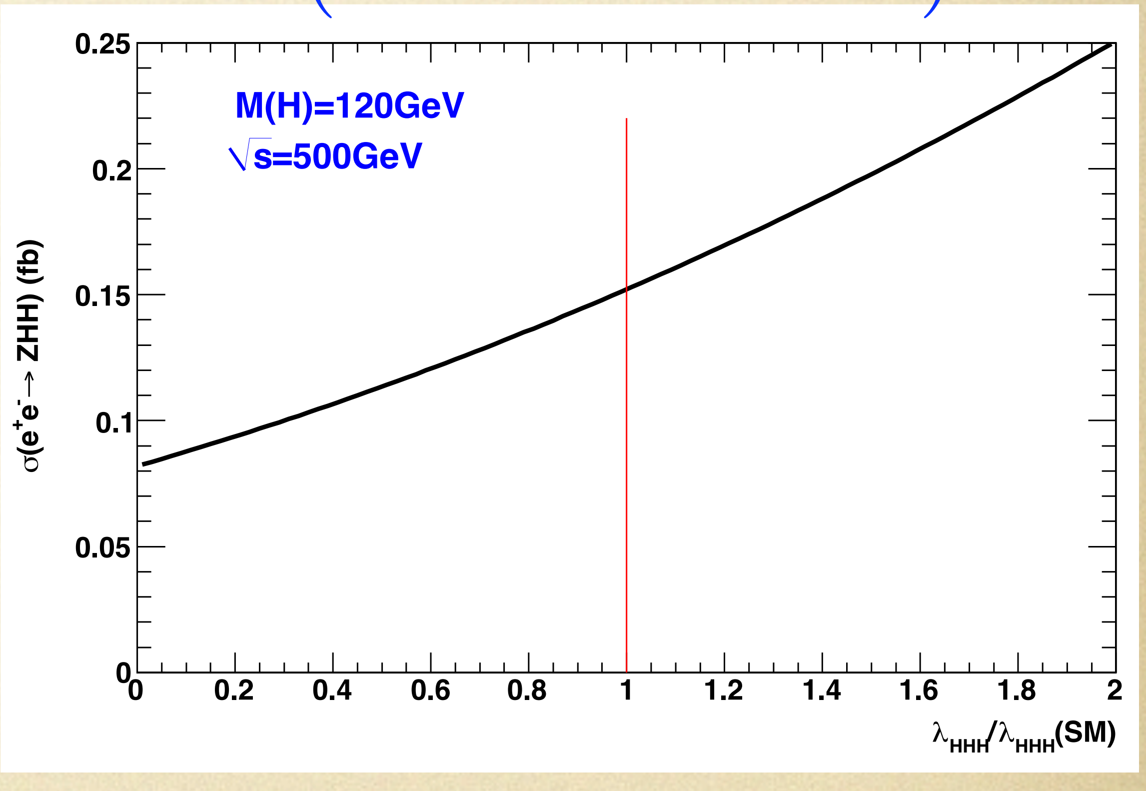
extraction of Higgs self-coupling from the cross section of ZHH

effect of irreducible diagram

$$\sigma = a\lambda^2 + b\lambda + c$$



$$\sigma(e^+e^- \to ZHH)$$



$$\frac{\Delta\lambda}{\lambda} = 1.8\frac{\Delta\sigma}{\sigma}$$

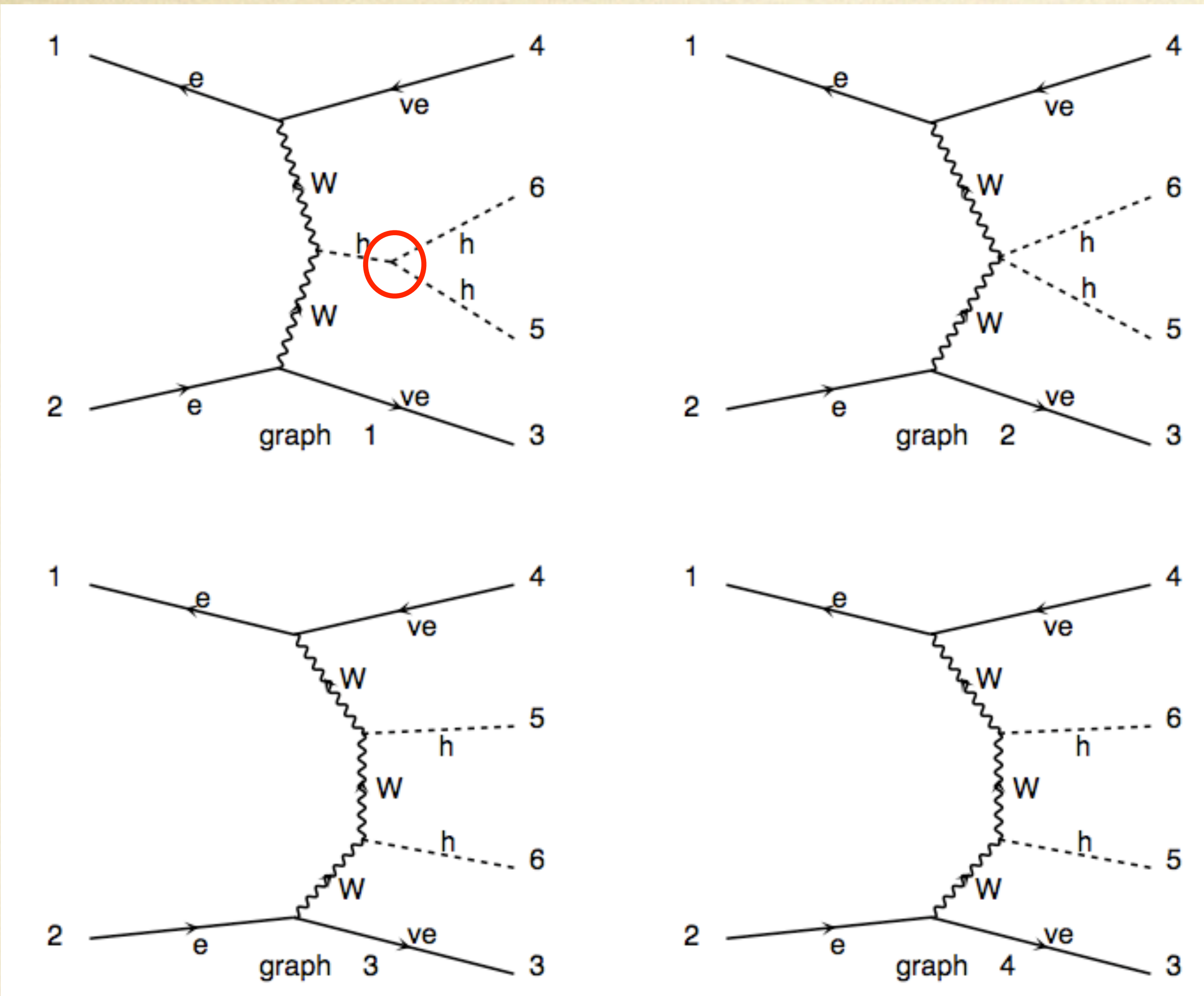
precision of self-coupling

precision of cross-section

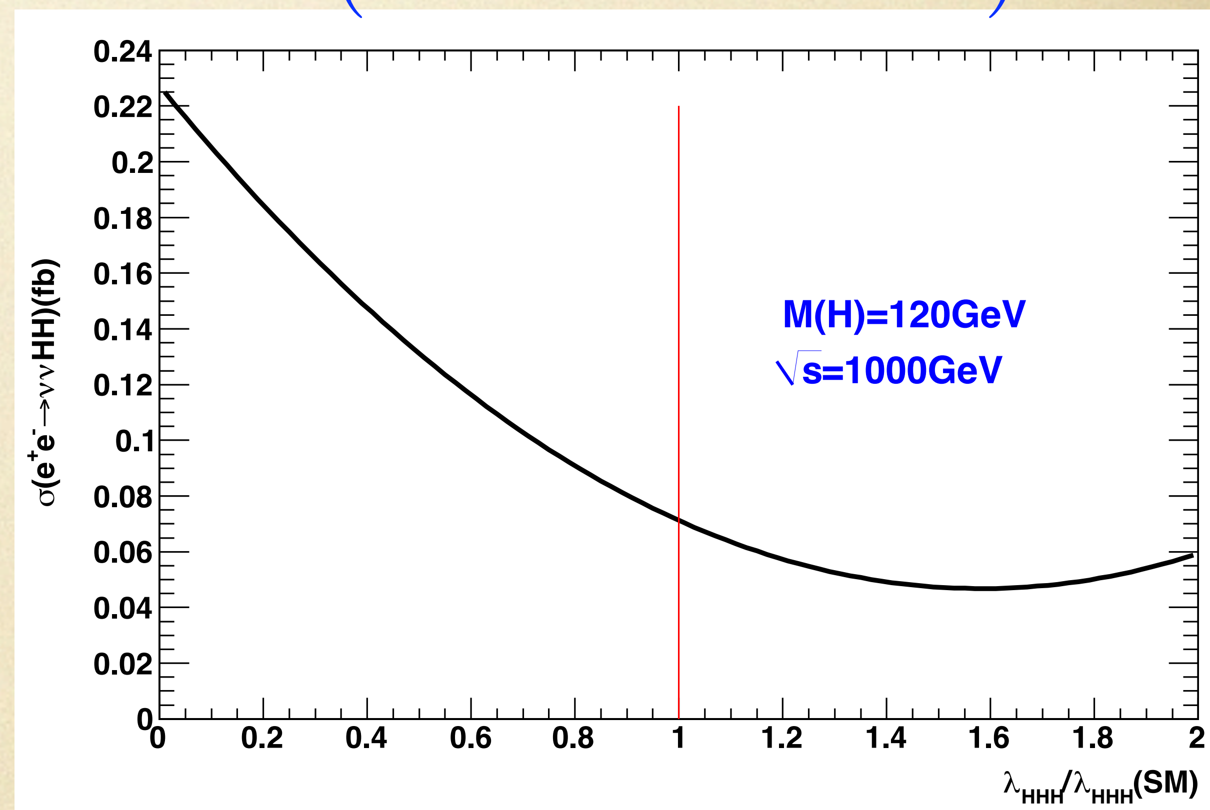
extraction of Higgs self-coupling from the cross section of υυHH

effect of irreducible diagram

$$\sigma = a\lambda^2 + b\lambda + c$$



$$\sigma(e^+e^- \to \nu\bar{\nu}\mathrm{HH})$$



$$\frac{\Delta\lambda}{\lambda} = 0.85\frac{\Delta\sigma}{\sigma}$$

precision of self-coupling

precision of cross-section

weighting

$$\lambda = -\frac{I_w}{2S_w} \pm \frac{\sqrt{I_w^2 - 4S_wB_w + 4S_w\sigma_w}}{2S_w}$$

$$\Delta\lambda|_{\lambda=\lambda_{SM}} = \frac{\Delta\sigma_w}{I_w + 2S_w} = \frac{\sqrt{\int \sigma(x)w^2(x)\mathrm{d}x}}{\int I(x)w(x)\mathrm{d}x + 2\int S(x)w(x)\mathrm{d}x}$$

→ **minimize the error of coupling** (variance principle)

equation of the optimal w(x):

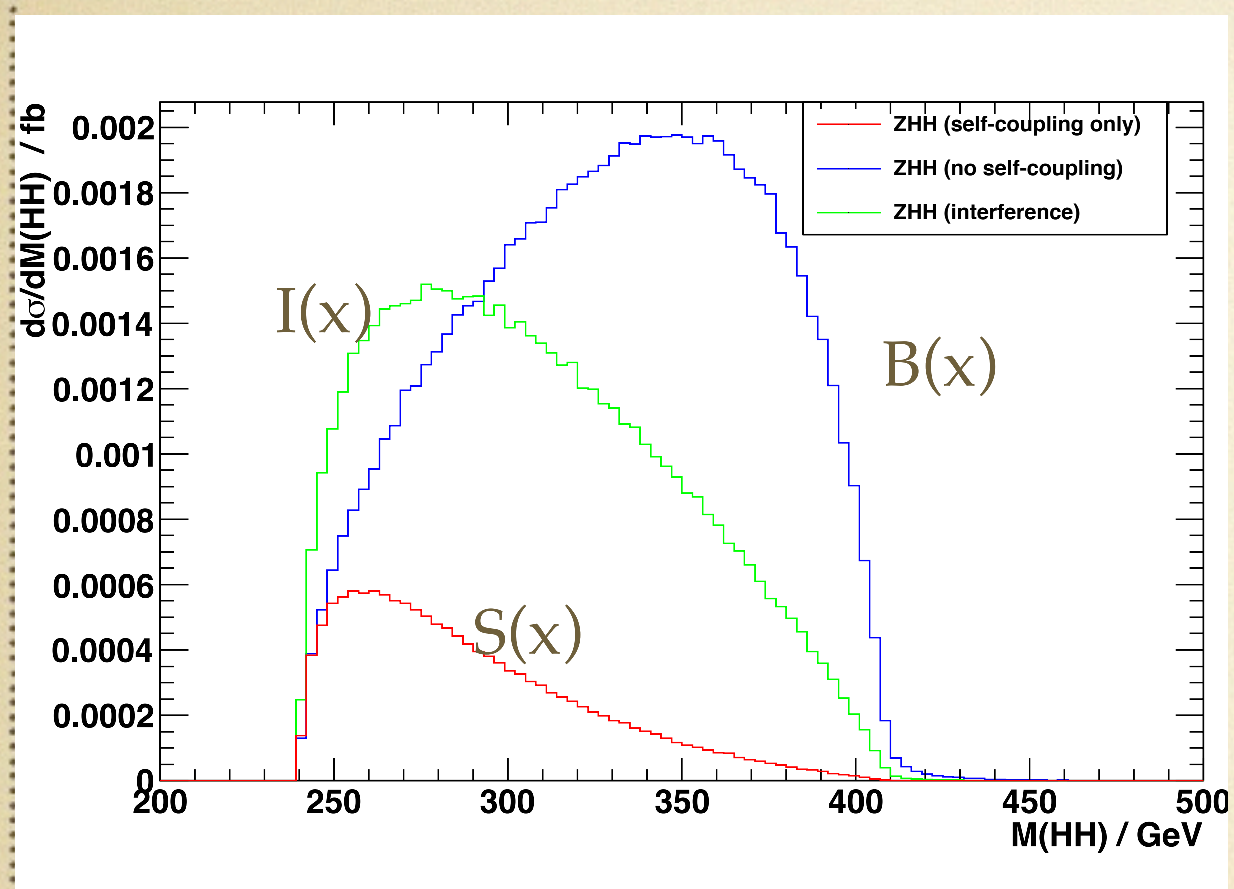
$$\sigma(x)w_0(x)\int(I(x)+2S(x))w_0(x)\mathrm{d}x = (I(x)+2S(x))\int\sigma(x)w_0^2(x)\mathrm{d}x$$

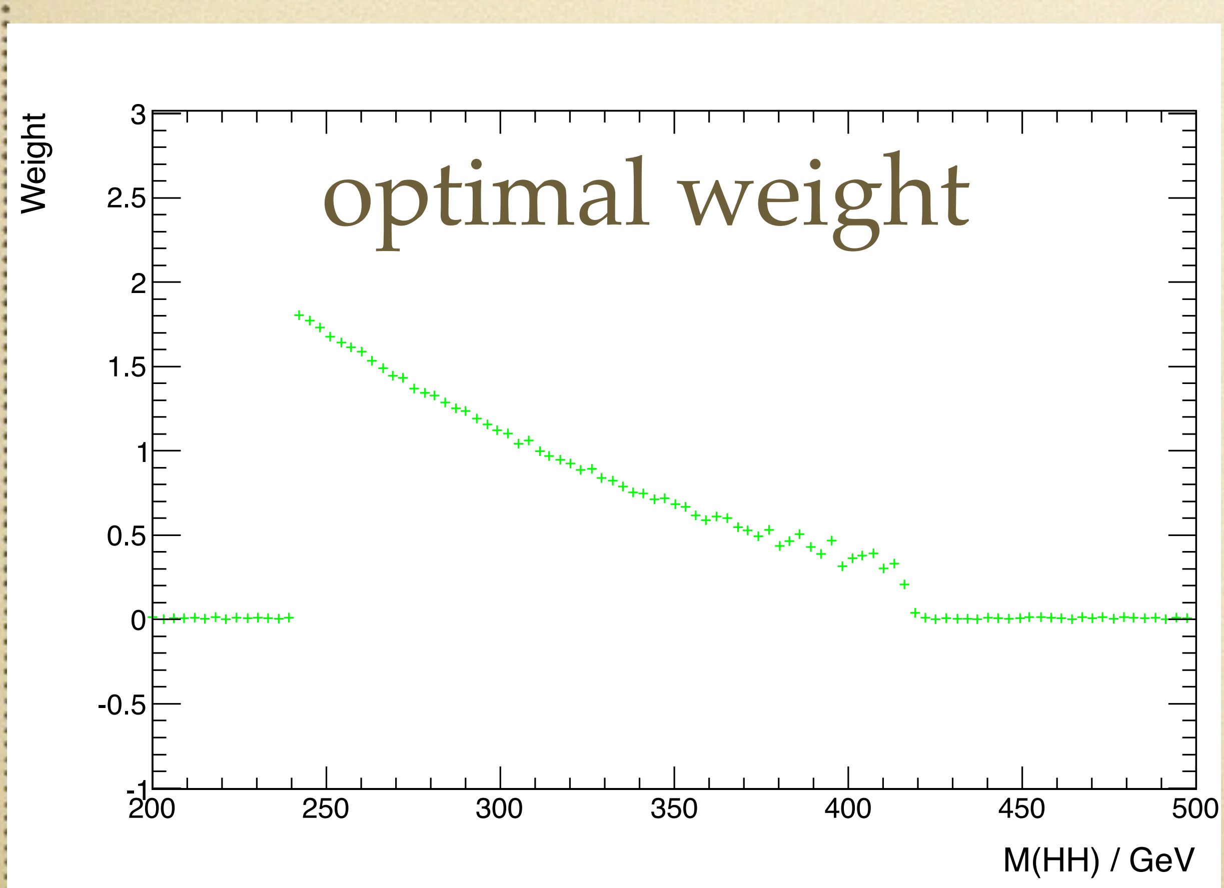
general solution:

$$w_0(x) = c\cdot\frac{I(x)+2S(x)}{\sigma(x)}$$

c: arbitrary normalization factor

weighting functions



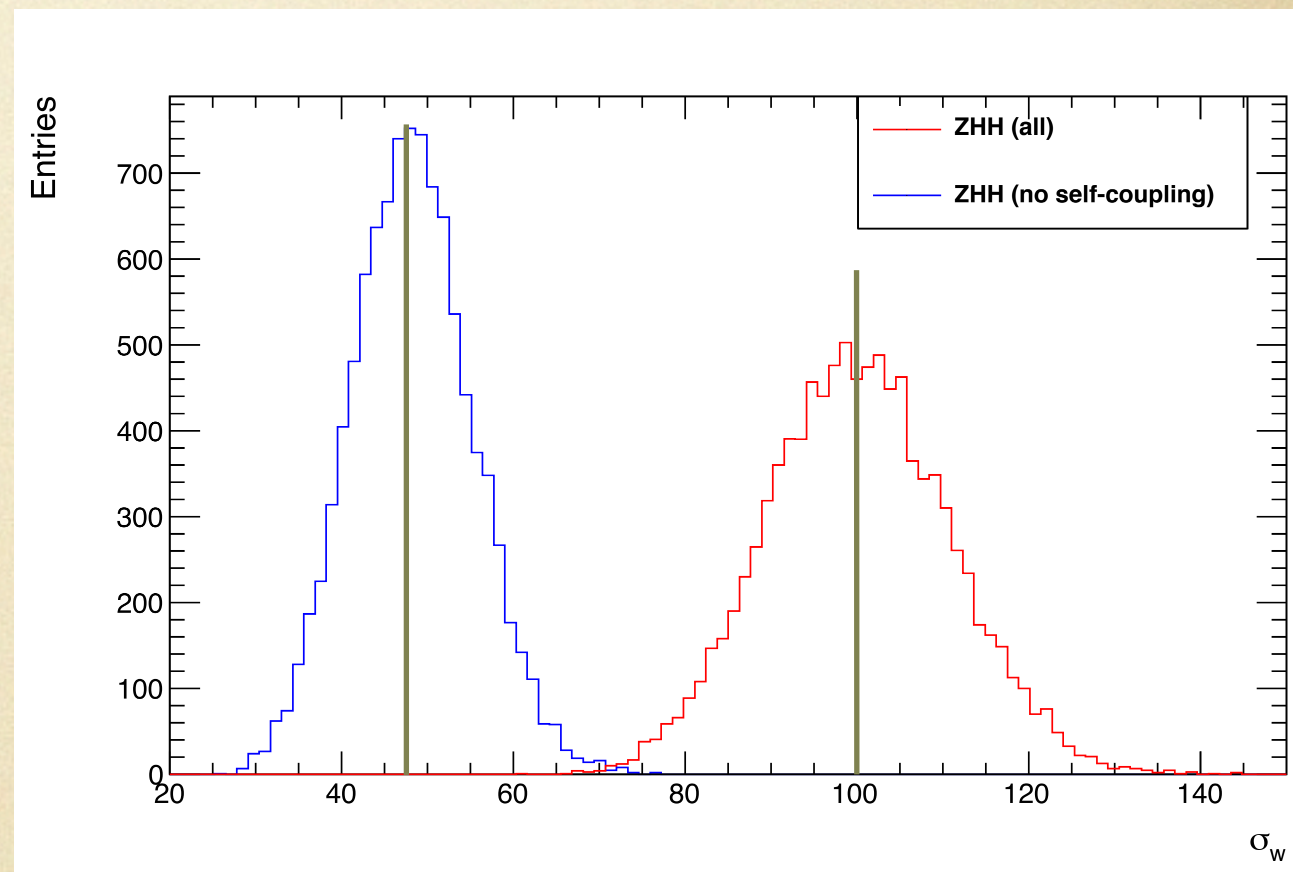


weighted cross section

(from toy monte-carlo)

assuming 100 signal events

(~54 from non-self-coupling)



at first ...

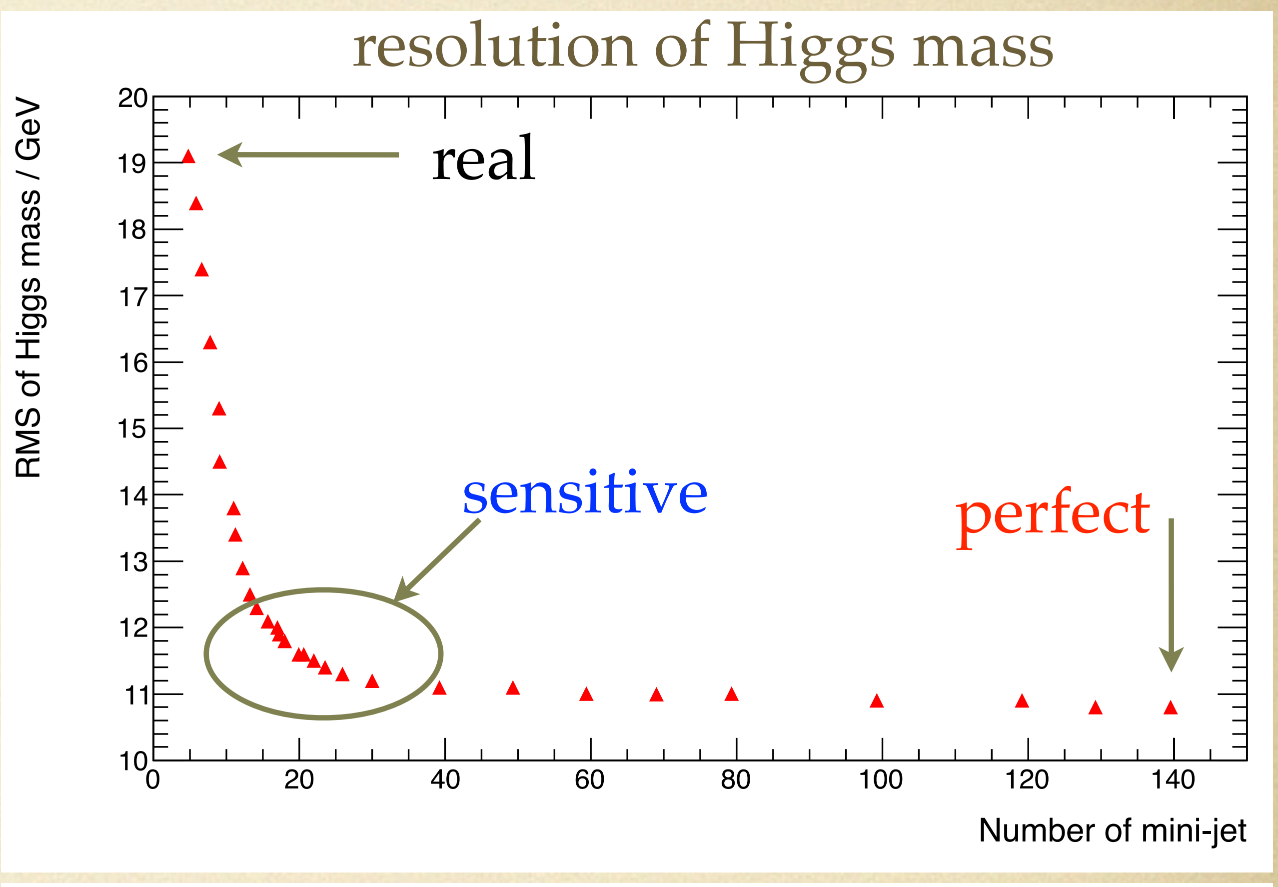
- Would the mini-jet be pure enough?
- When would the mini-jet clustering appropriately stop?

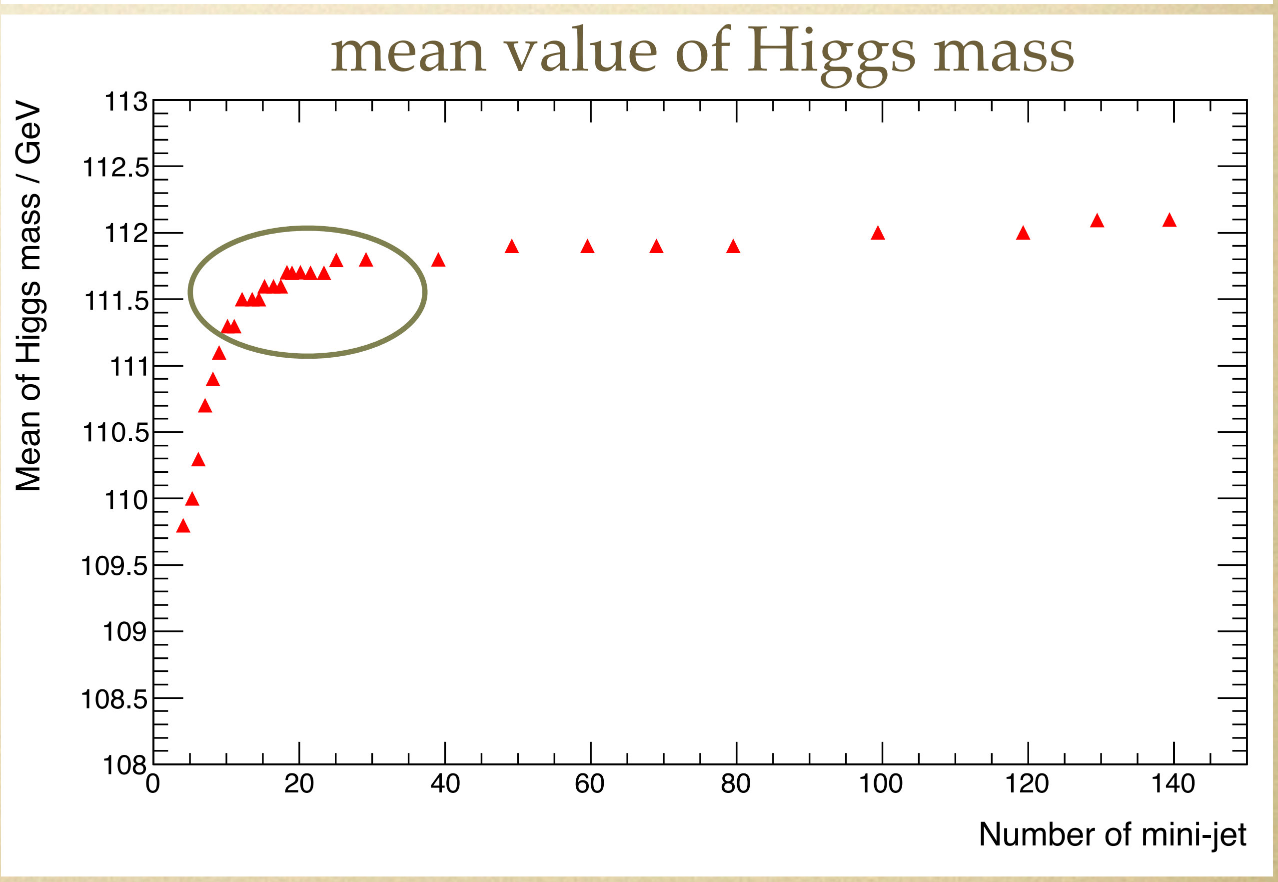
these can be tested supposing we can combine the mini-jets perfectly

vvHH ---> vvbbbb

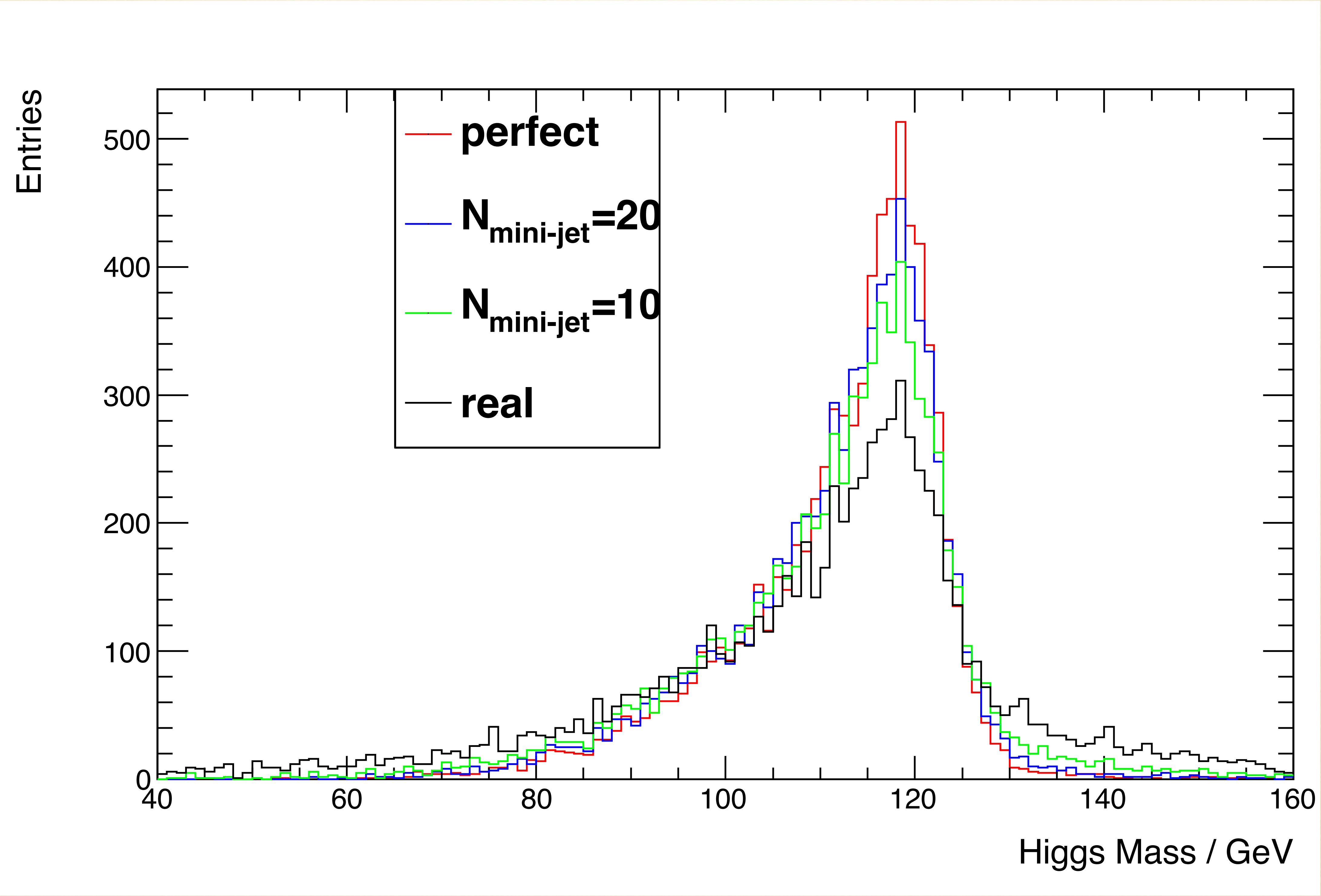
- using the realistic Duhram algorithm for the mini-jet clustering, stop when there are fixed number of mini-jets left.
- combine the mini-jets with cheated information, check the performance of Higgs reconstruction

(two Higgs masses are merged)





at first ...



Entries
500
400
300
200
100
0
40
60
80
100
120
140
160
Higgs Mass / GeV
perfect
N mini-jet=20
N mini-jet=10
real